The Zero-Marginal Cost Power Grid

ESIF Workshop on Frontiers in Distributed Optimization and Control of Sustainable Power Systems

National Renewable Energy Laboratory – January 27-28, 2016

Sean P. Meyn

Florida Institute for Sustainable Energy

Department of Electrical and Computer Engineering — University of Florida

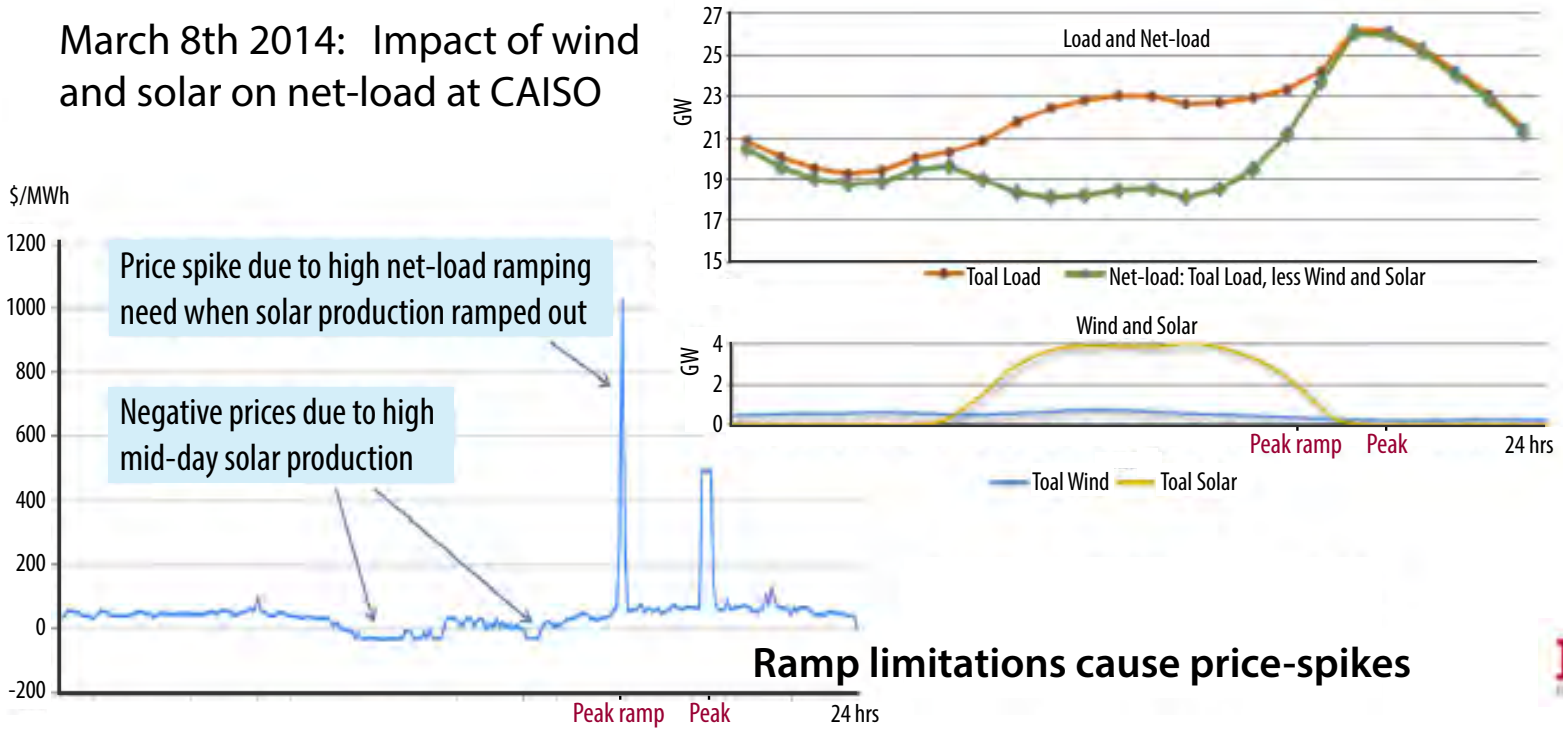
Thanks to my colleagues, Profs. Prabir Barooah and Ana Bušić
Special thanks to (soon-to-graduate) Yue Chen
and to our sponsors

Google, NSF, DOE

Zero-Marginal Cost Grid

Outline

March 8th 2014: Impact of wind and solar on net-load at CAISO



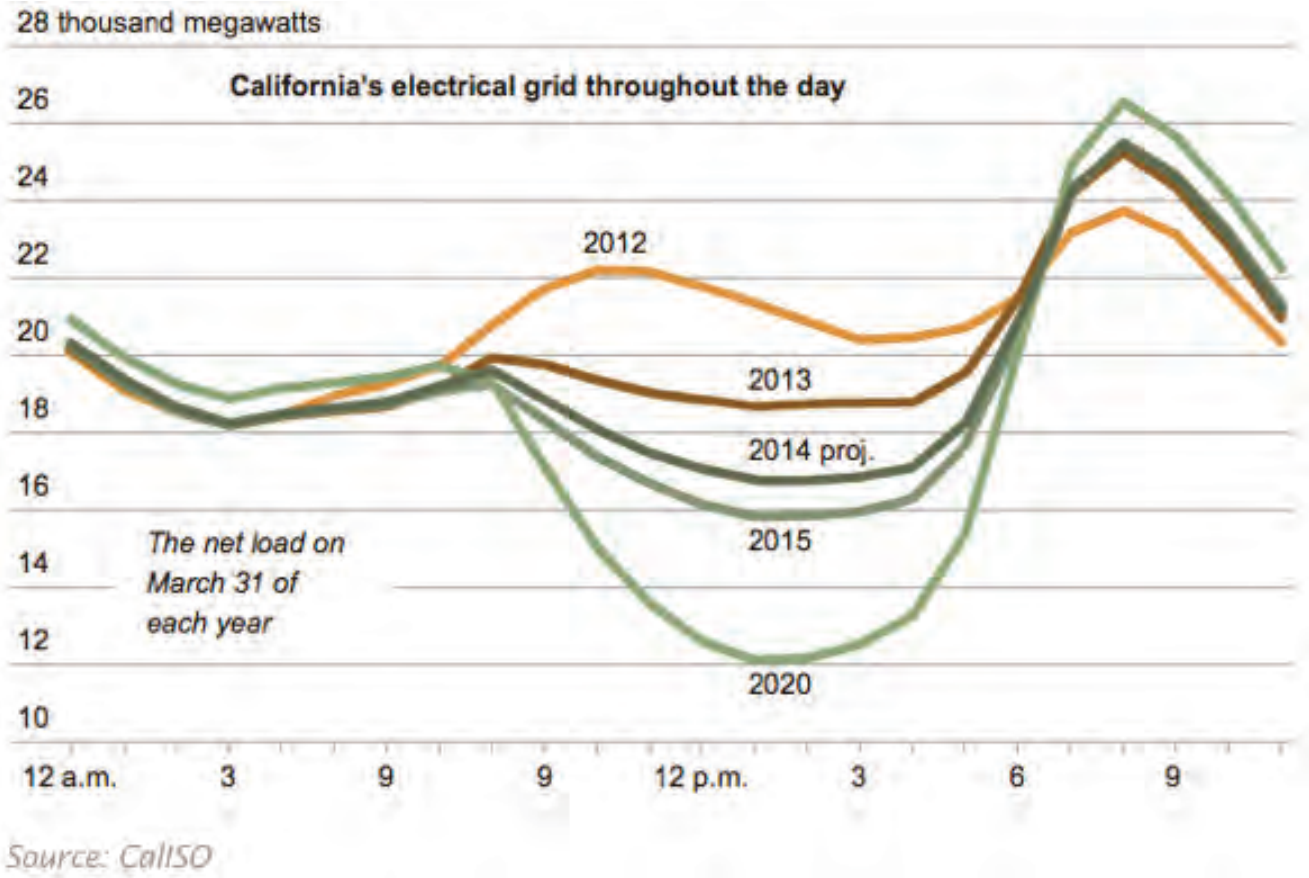
Ramp limitations cause price-spikes

PCI

Challenges

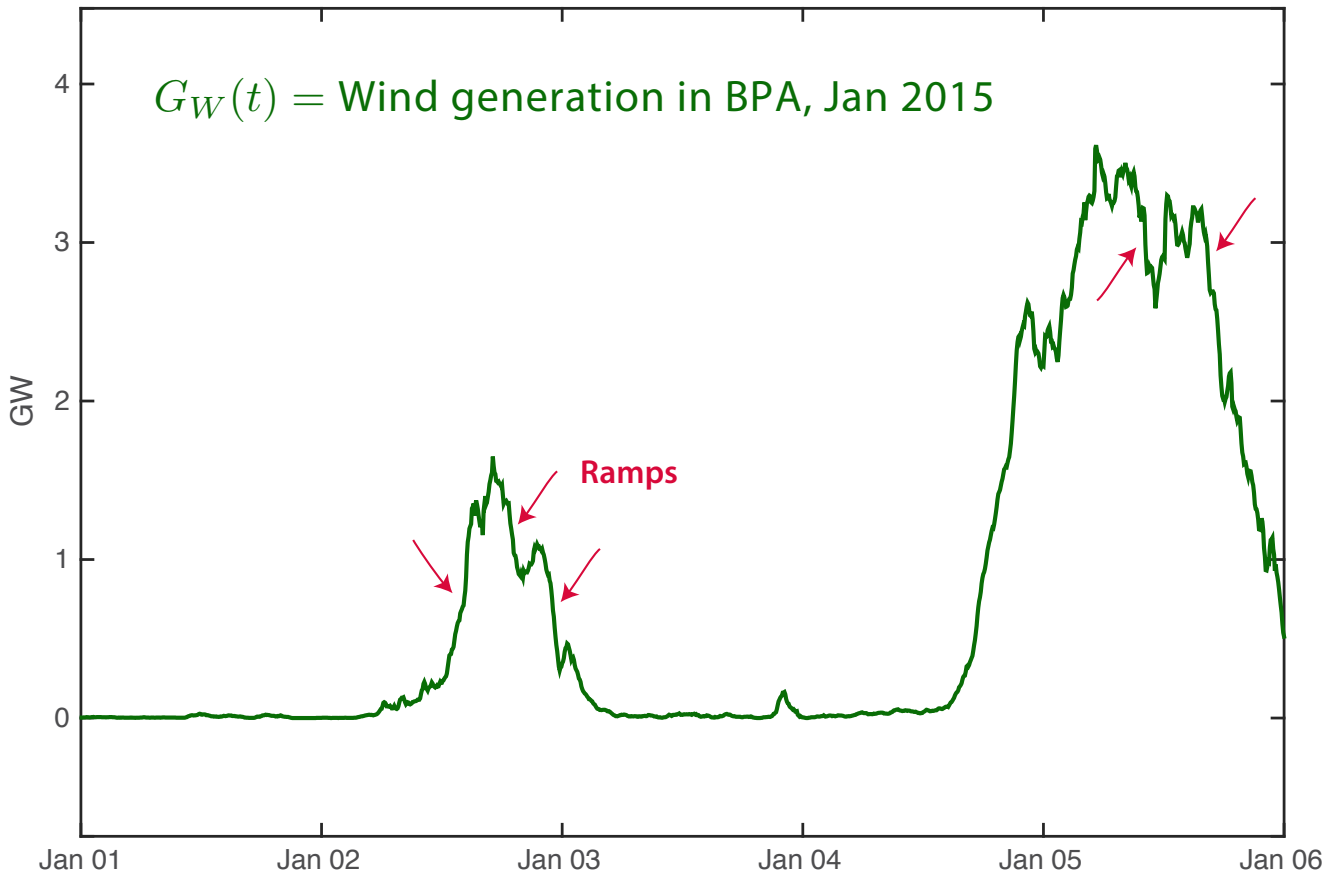
Some of the Challenges

1. Ducks



Some of the Challenges

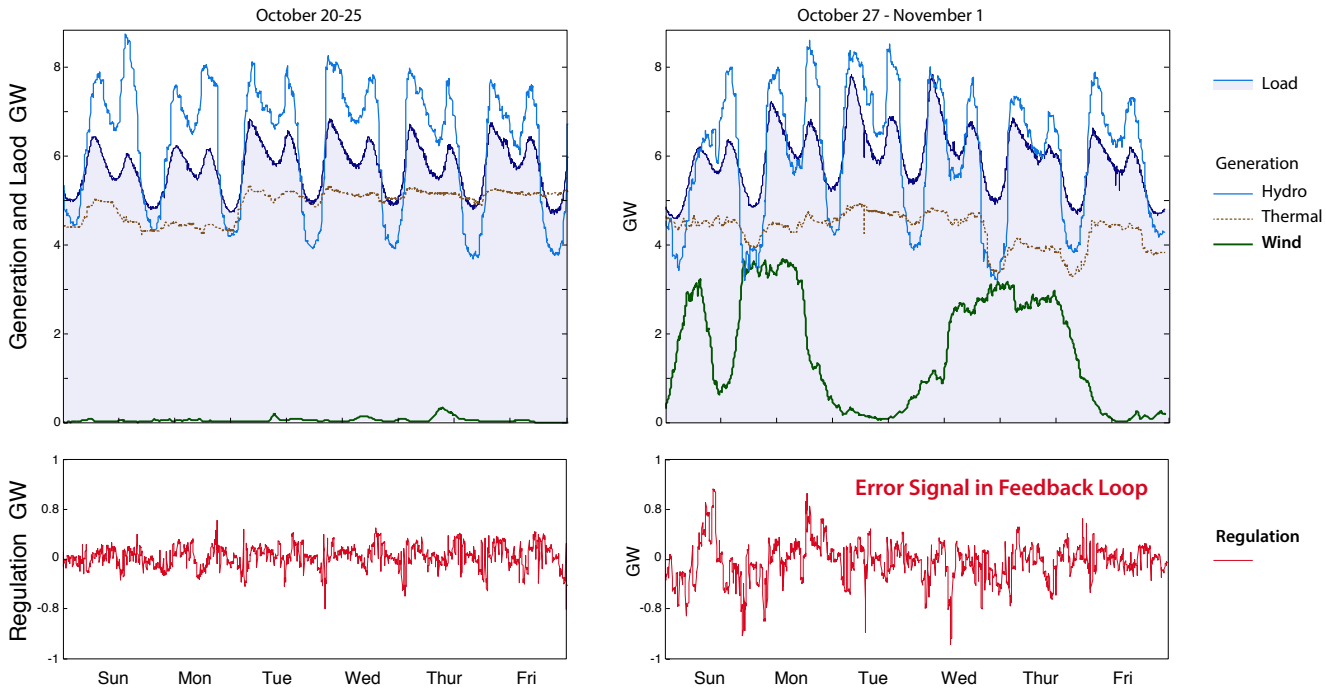
1. Ducks
2. Ramps



MISO, CAISO, and others are introducing markets for *ramping products*

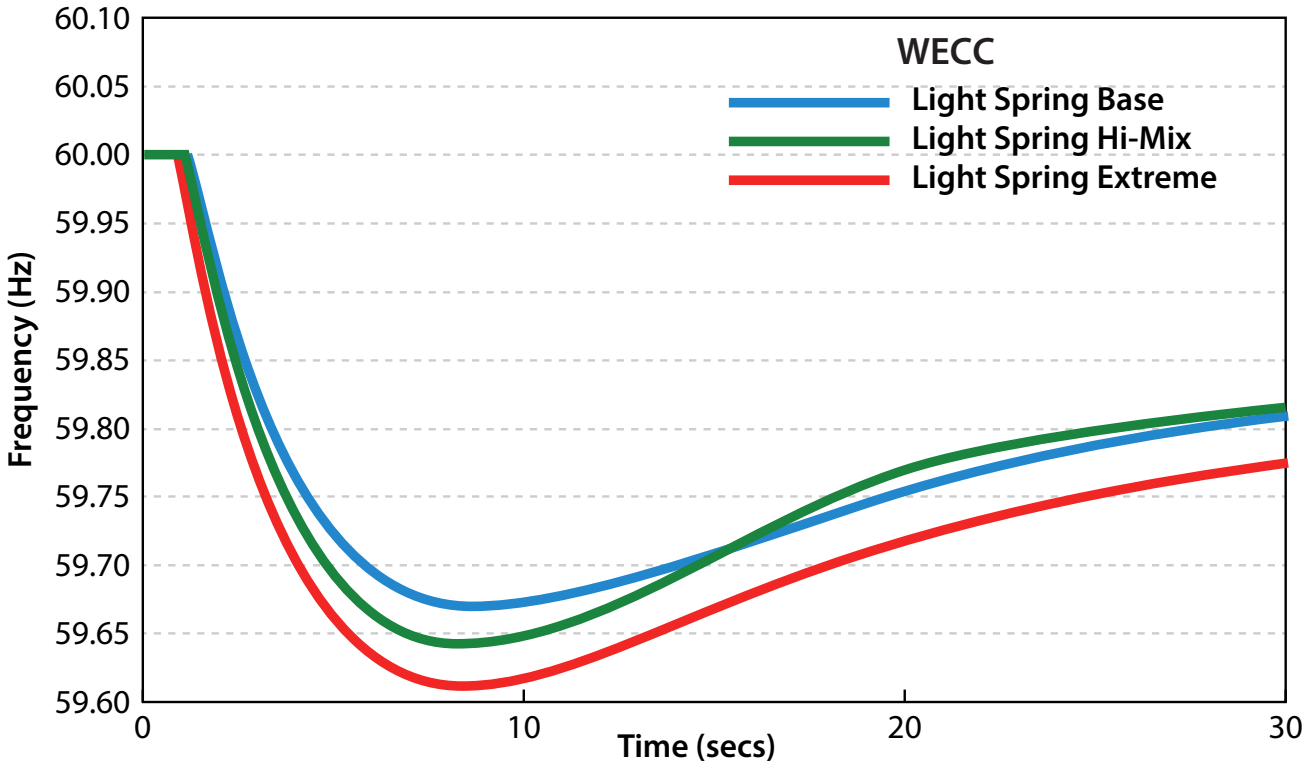
Some of the Challenges

1. Ducks
2. Ramps
3. Regulation



Some of the Challenges

1. Ducks
2. Ramps
3. Regulation
4. Contingency



Some of the Challenges

1. Ducks
2. Ramps
3. Regulation
4. Contingency

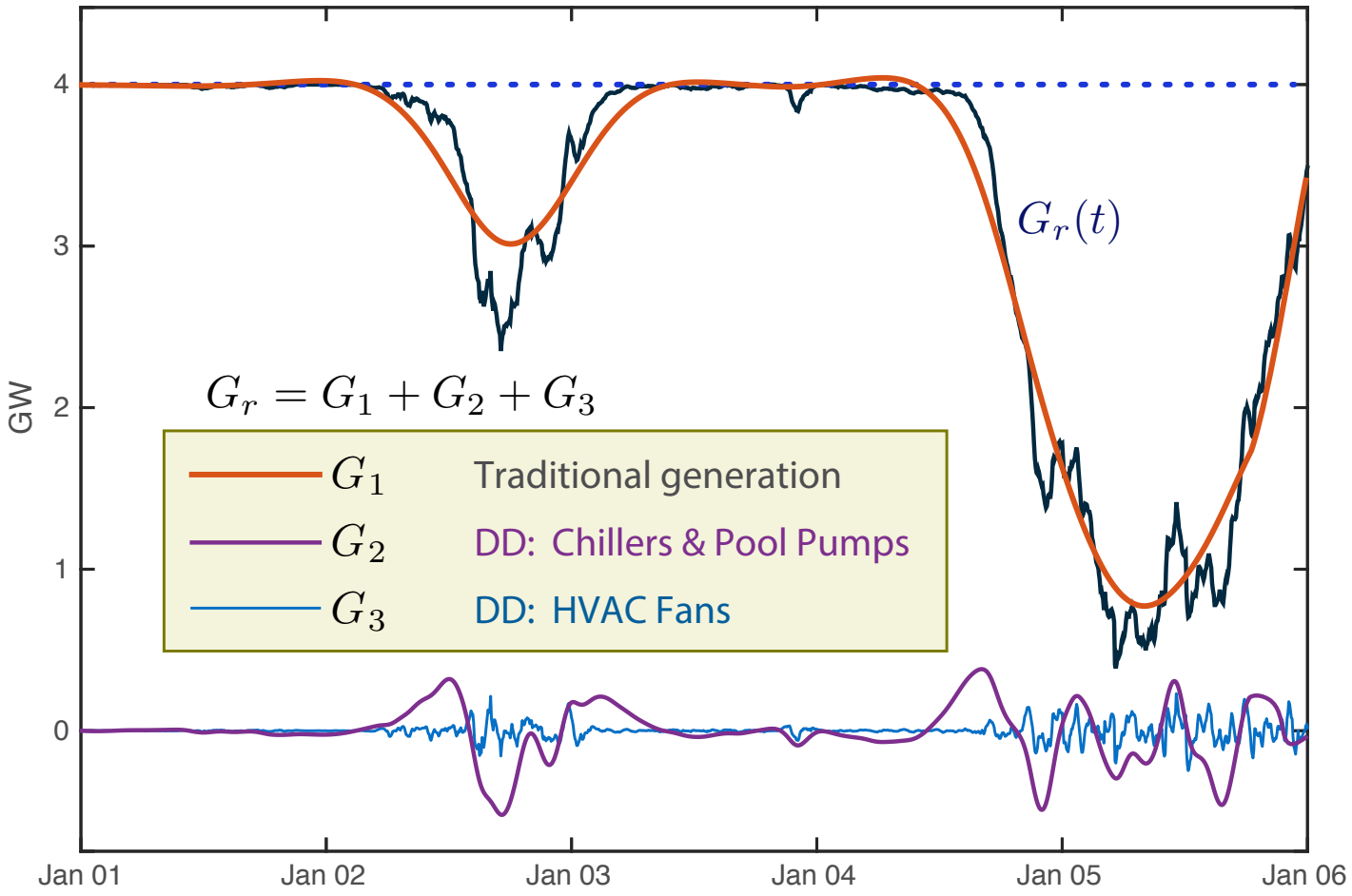
Q: Which of these has anything to do with energy?

Some of the Challenges

1. Ducks
2. Ramps
3. Regulation
4. Contingency

Q: Which of these has anything to do with energy?

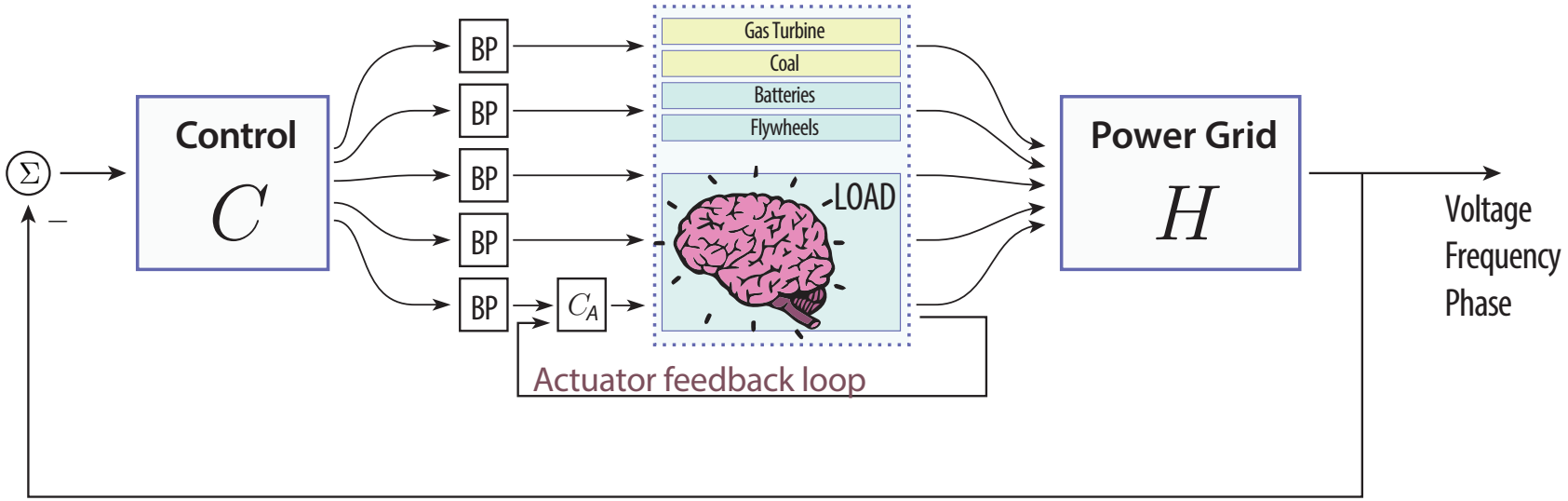
A: **none**!



Ancillary Service – *free, like Digital Music*

Control Architecture

Frequency Decomposition

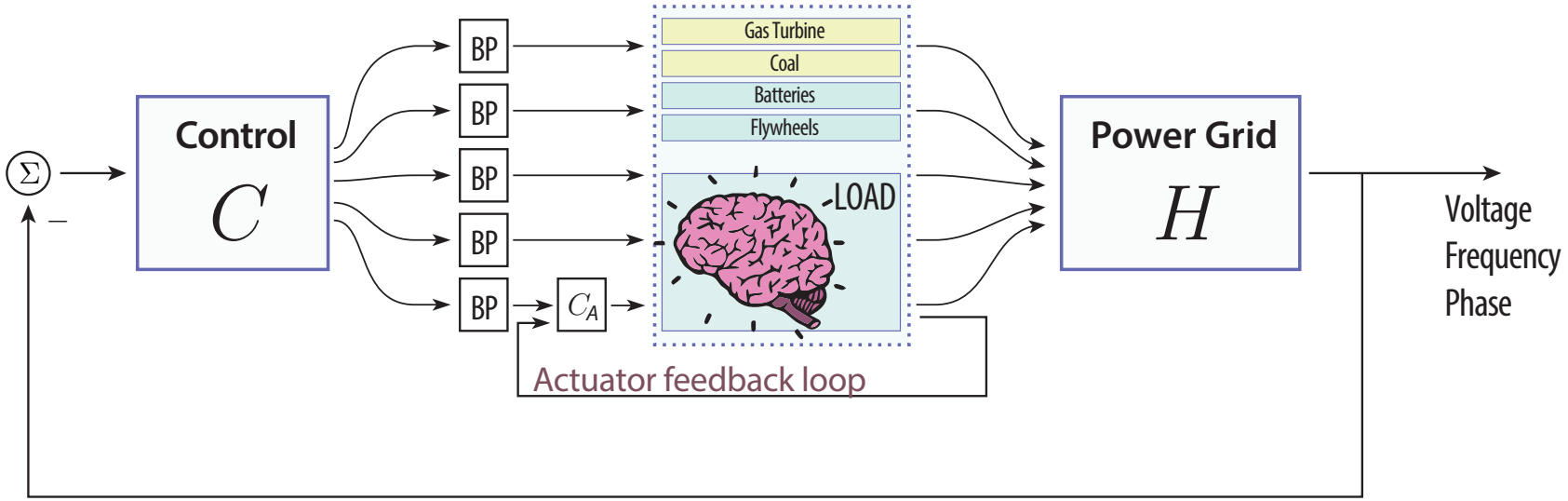


Today: PJM decomposes regulation signal based on bandwidth,

$$\mathrm{R} = \mathrm{RegA} + \cdots + \mathrm{RegD}$$

Control Architecture

Frequency Decomposition



Today: PJM decomposes regulation signal based on bandwidth,

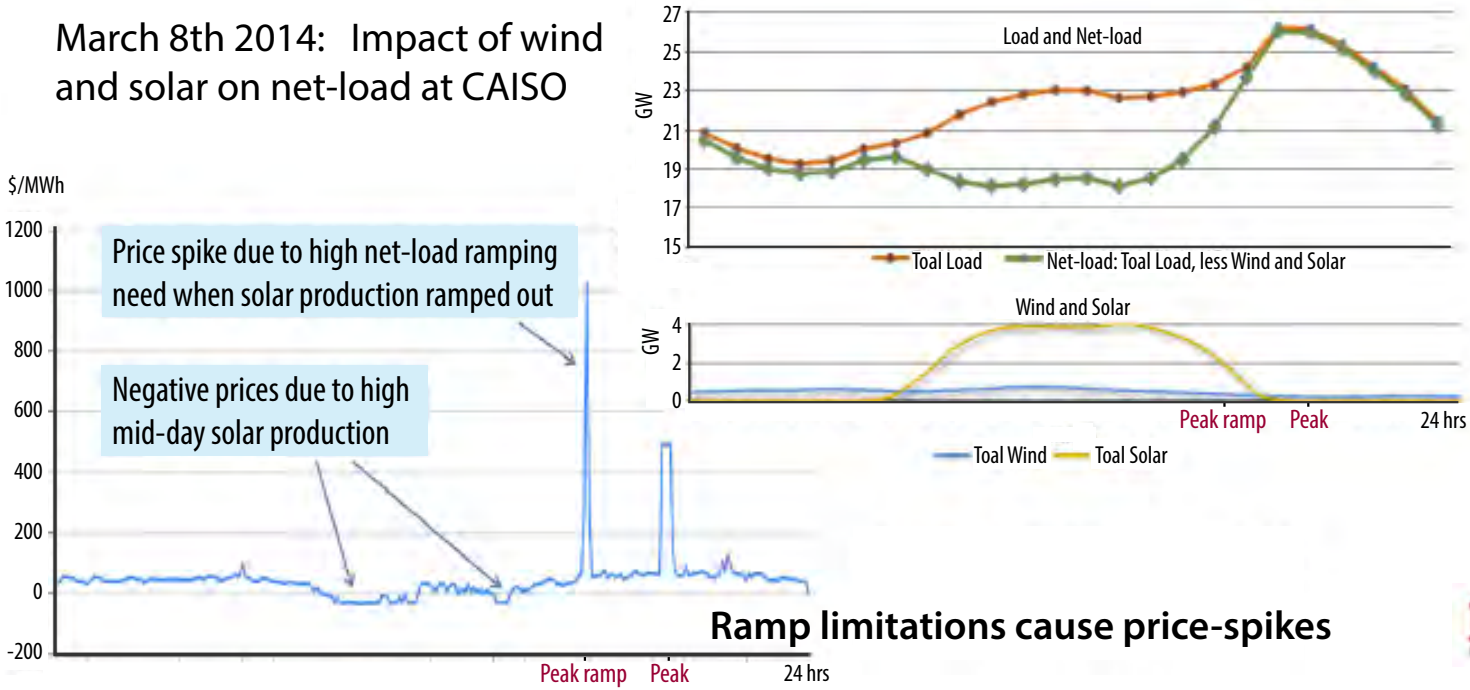
$$\mathrm{R} = \mathrm{RegA} + \cdots + \mathrm{RegD}$$

Proposal: Each class of DR (and other) resources will have its own bandwidth of service, based on QoS constraints and costs.

Frequency Decomposition

Taming the Duck

March 8th 2014: Impact of wind and solar on net-load at CAISO

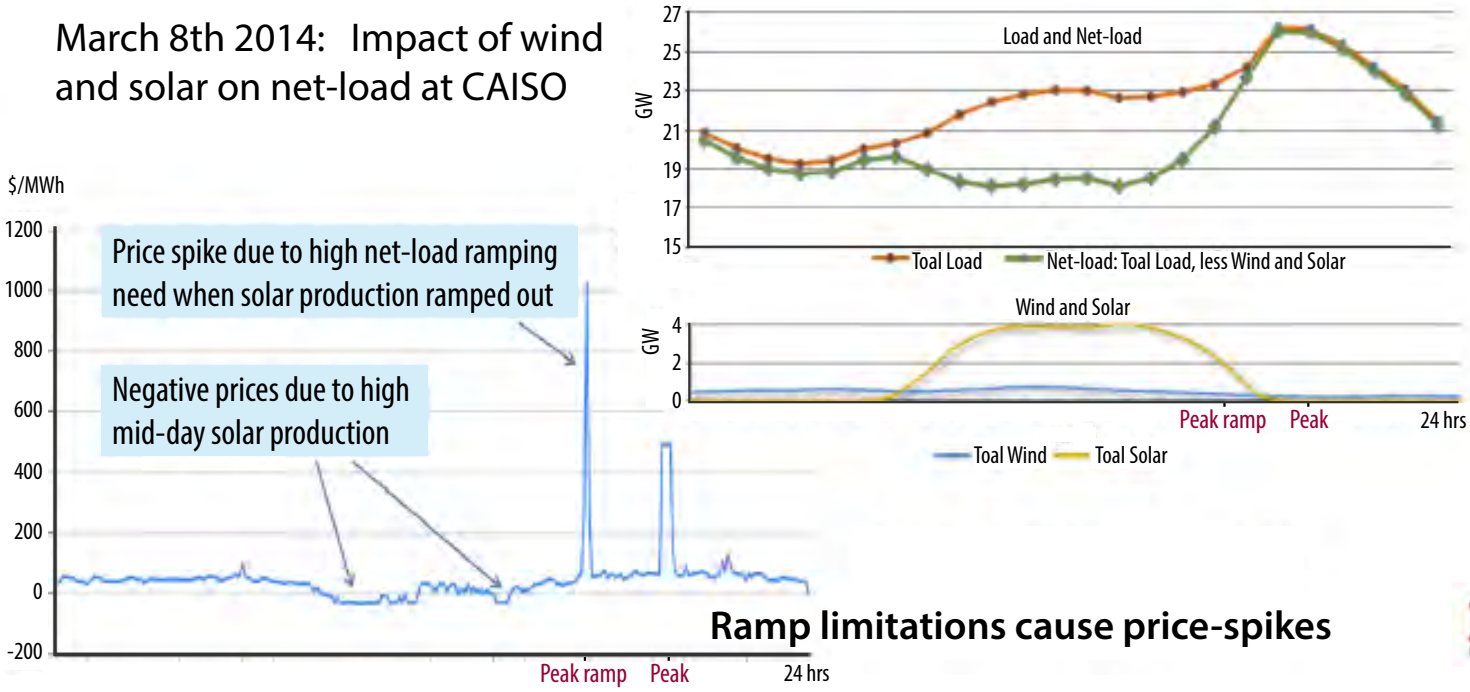


Ramp limitations cause price-spikes

Frequency Decomposition

Taming the Duck

March 8th 2014: Impact of wind and solar on net-load at CAISO



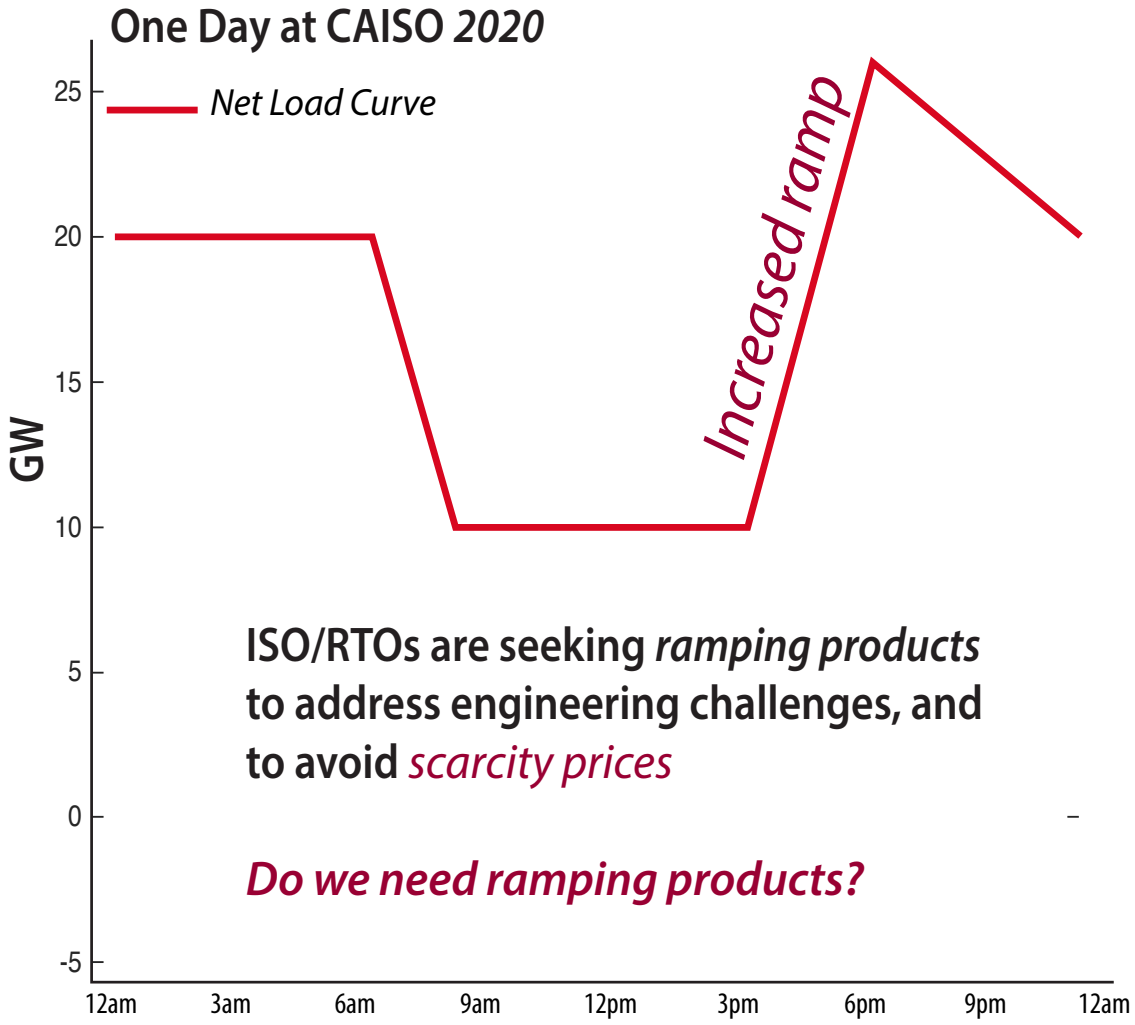
Ramp limitations cause price-spikes

ISOs need help:... *ramp capability shortages could result in a single, five-minute dispatch interval or multiple consecutive dispatch intervals during which the price of energy can increase significantly due to scarcity pricing, even if the event does not present a significant reliability risk*

http://tinyurl.com/FERC-ER14-2156-000

Frequency Decomposition

Taming the Duck

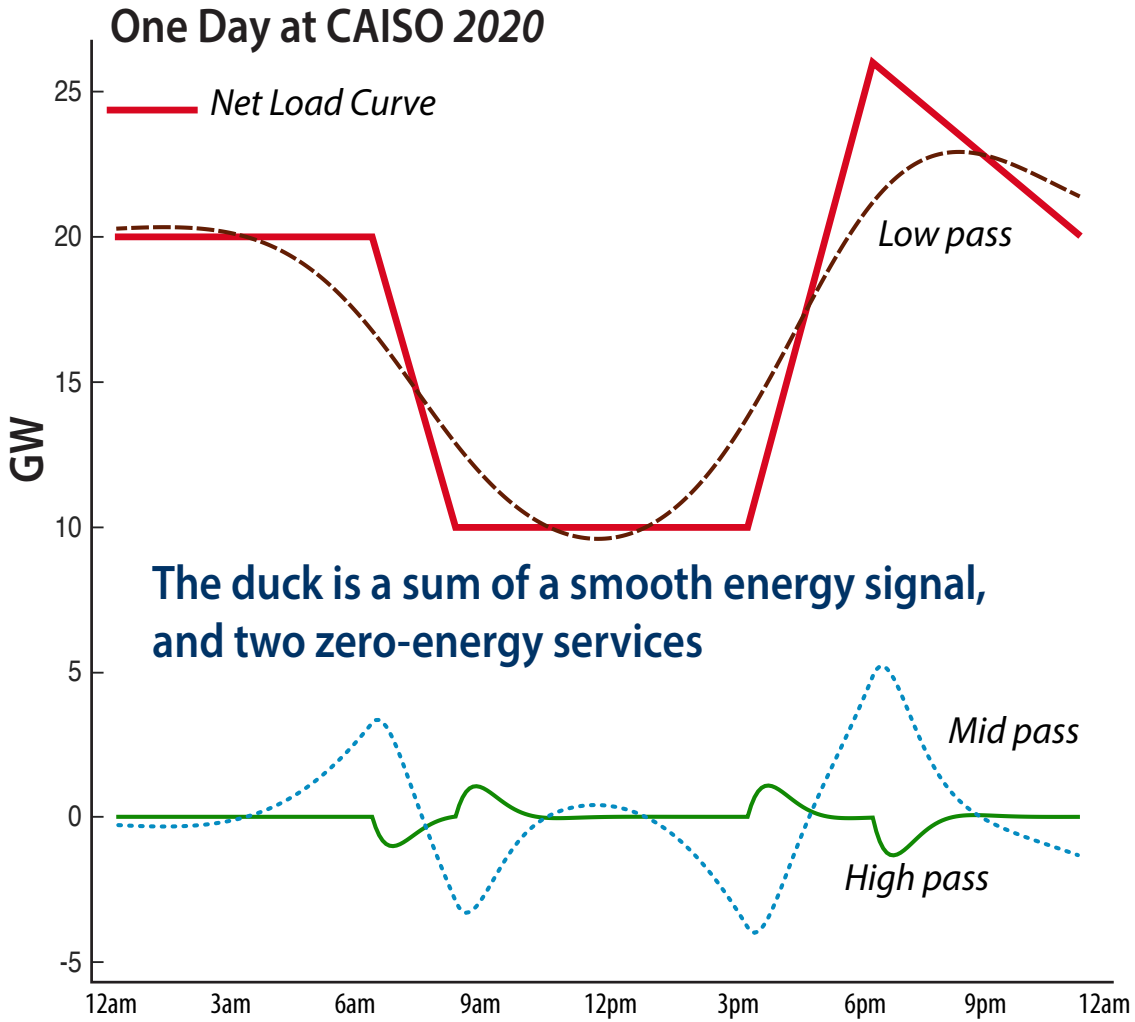


Frequency Decomposition

Taming the Duck

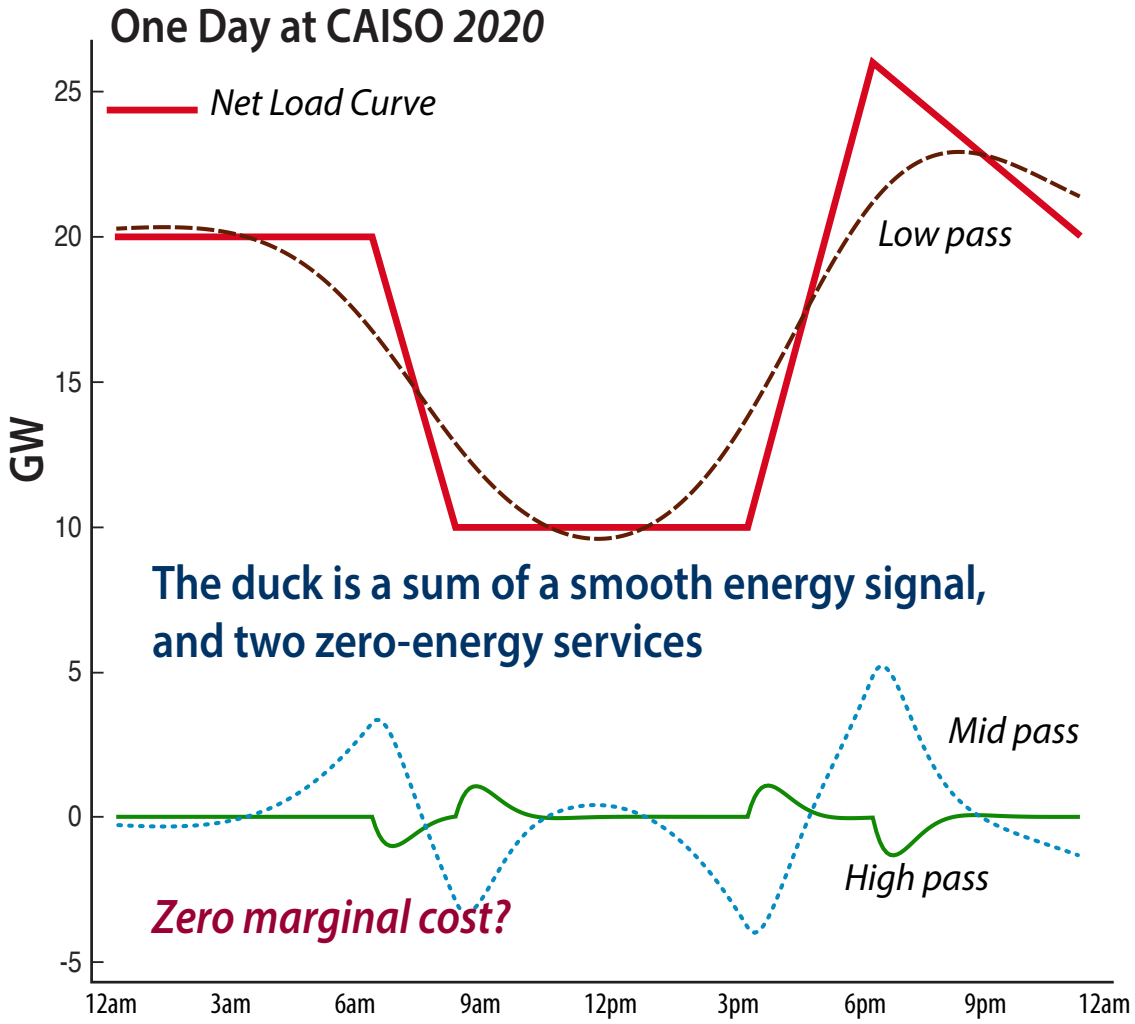
Frequency Decomposition

Taming the Duck



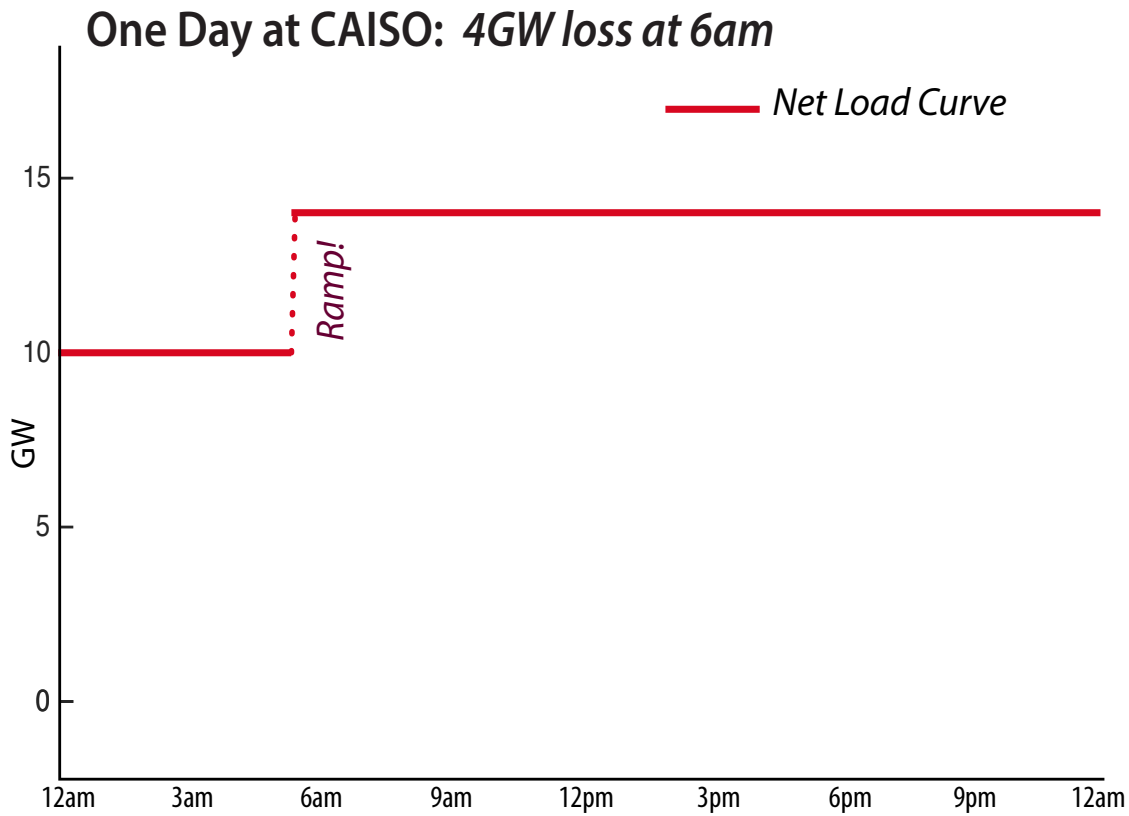
Frequency Decomposition

Taming the Duck



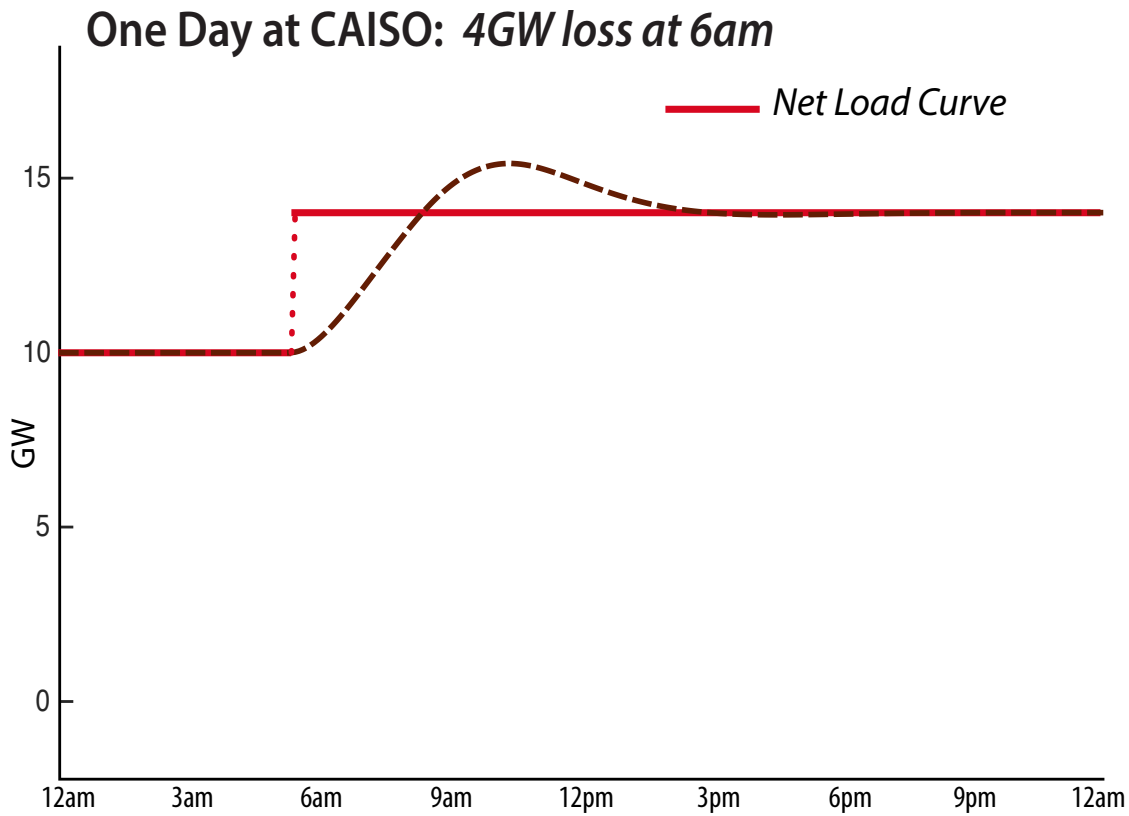
Frequency Decomposition

Smoothing Contingencies



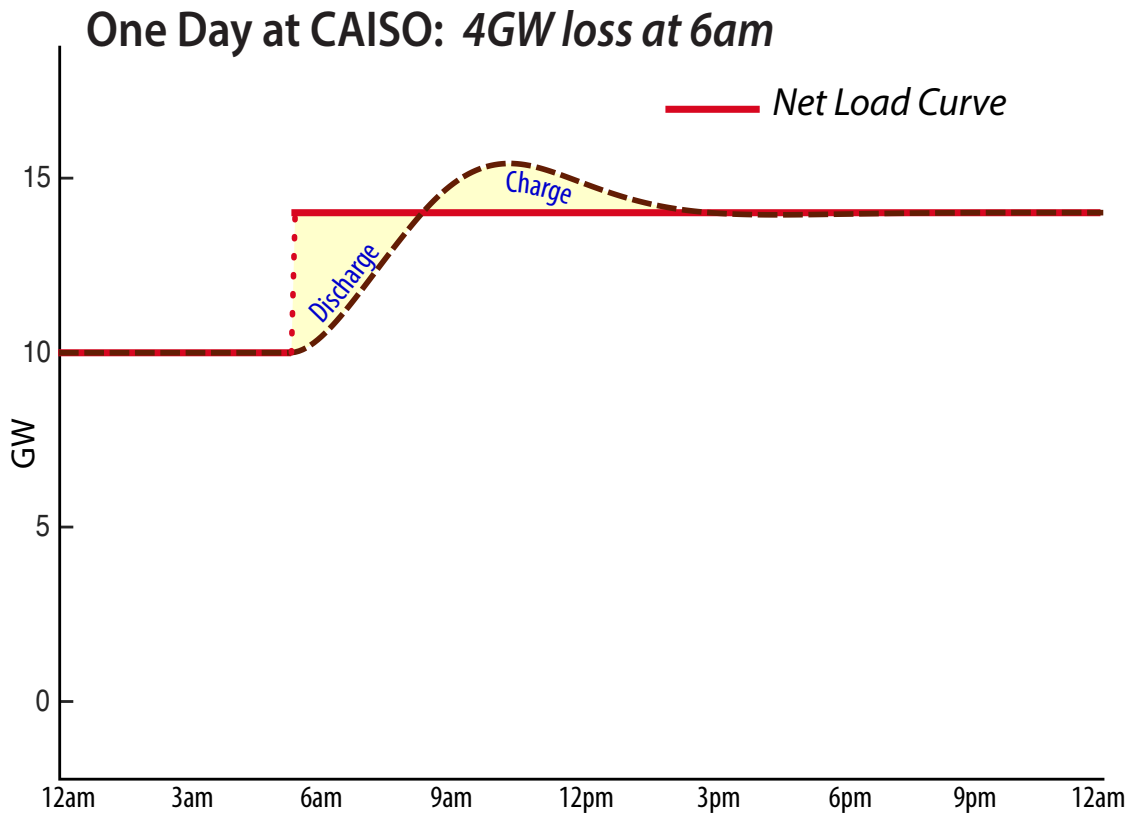
Frequency Decomposition

Smoothing Contingencies



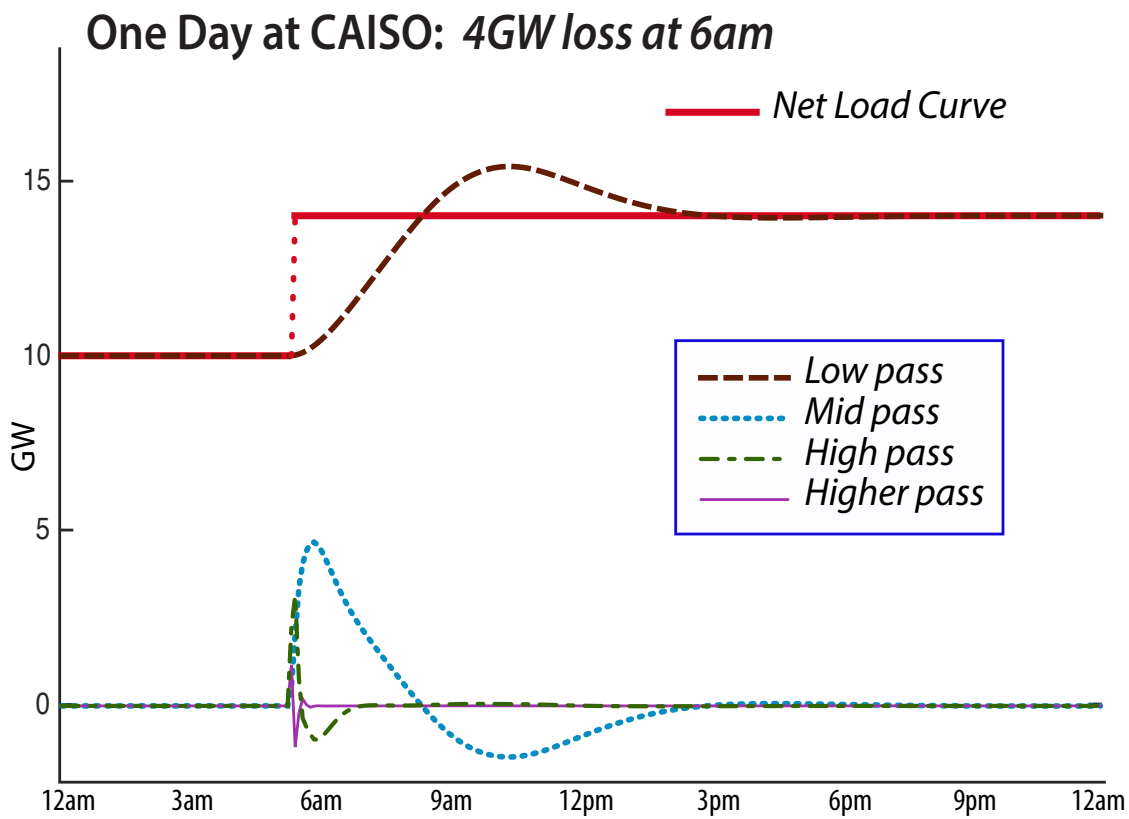
Frequency Decomposition

Smoothing Contingencies



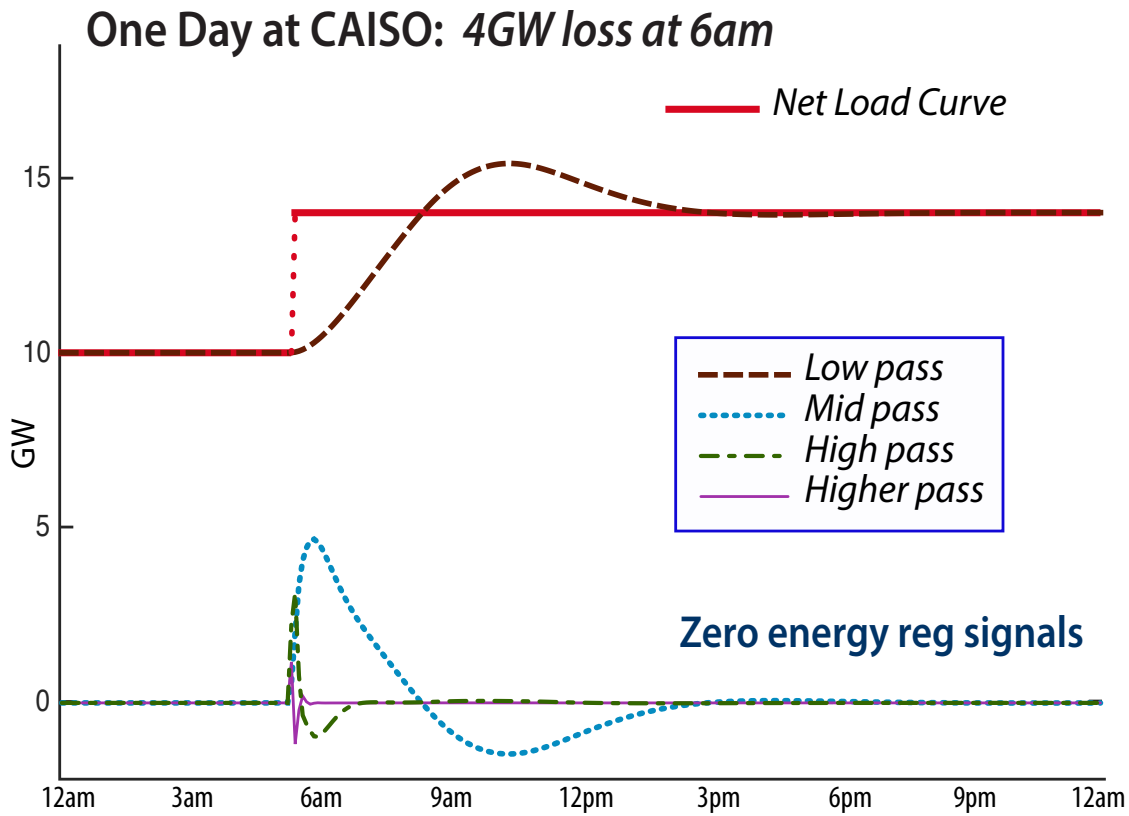
Frequency Decomposition

Smoothing Contingencies



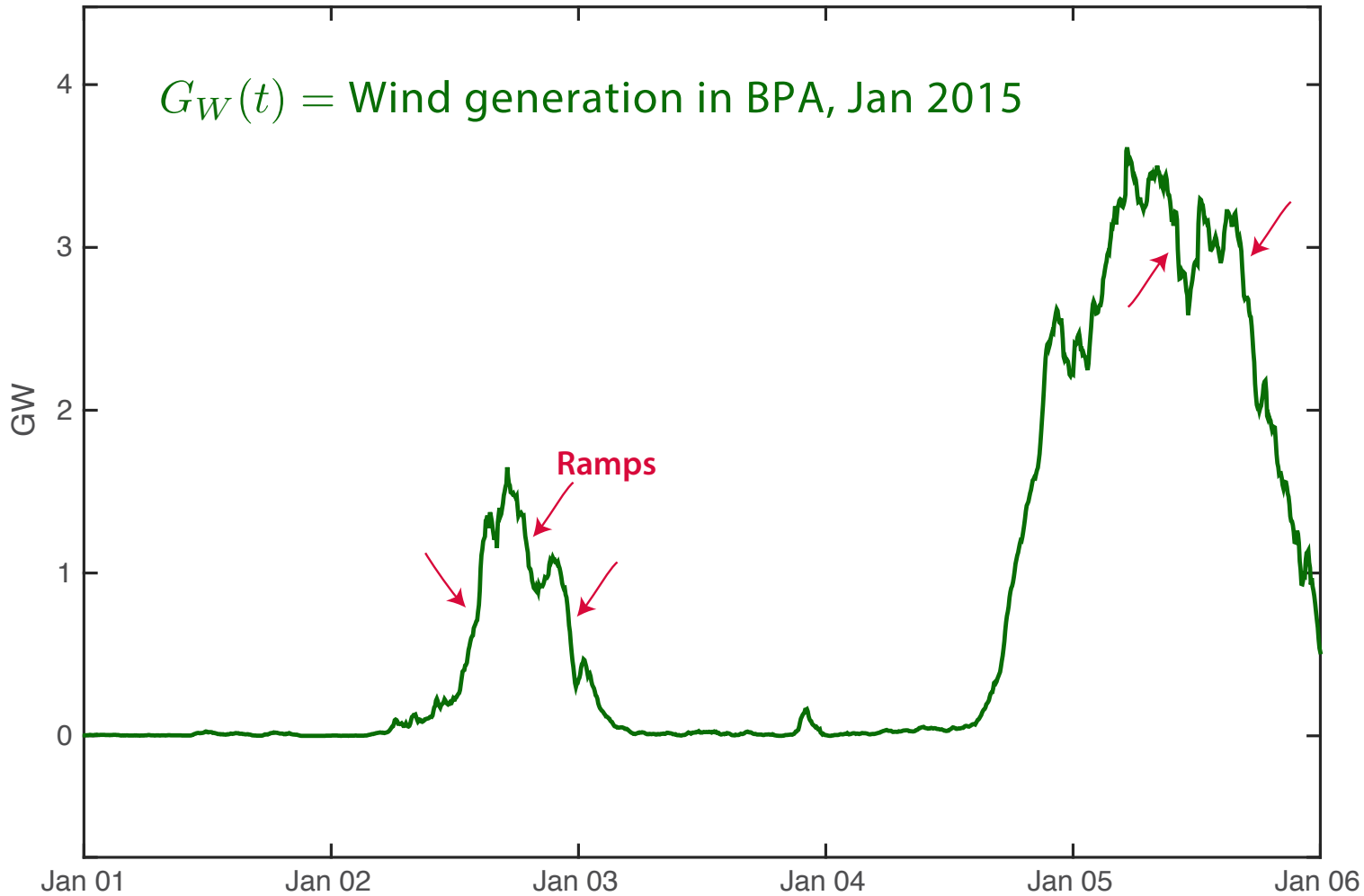
Frequency Decomposition

Smoothing Contingencies



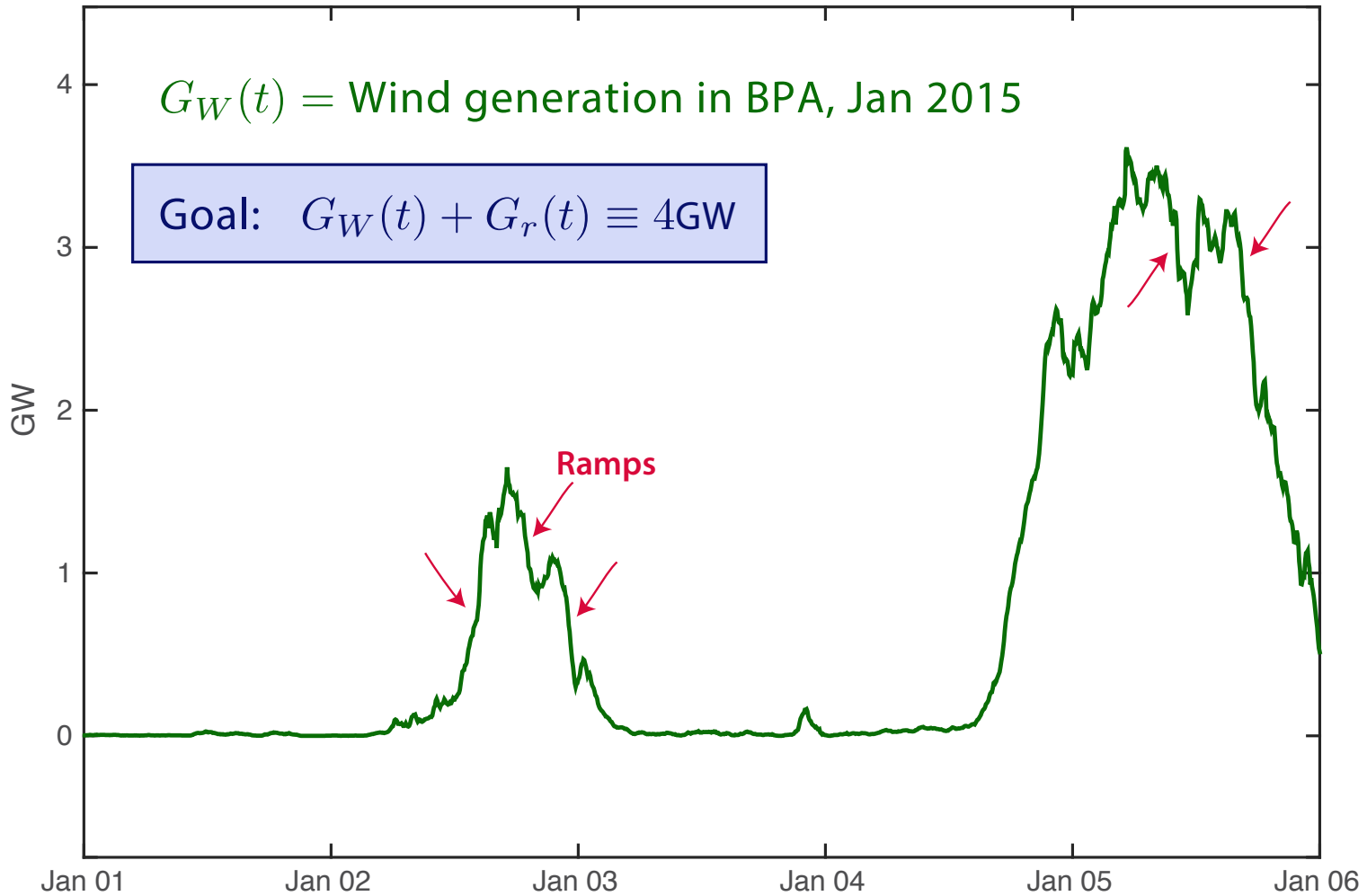
Frequency Decomposition

Regulation



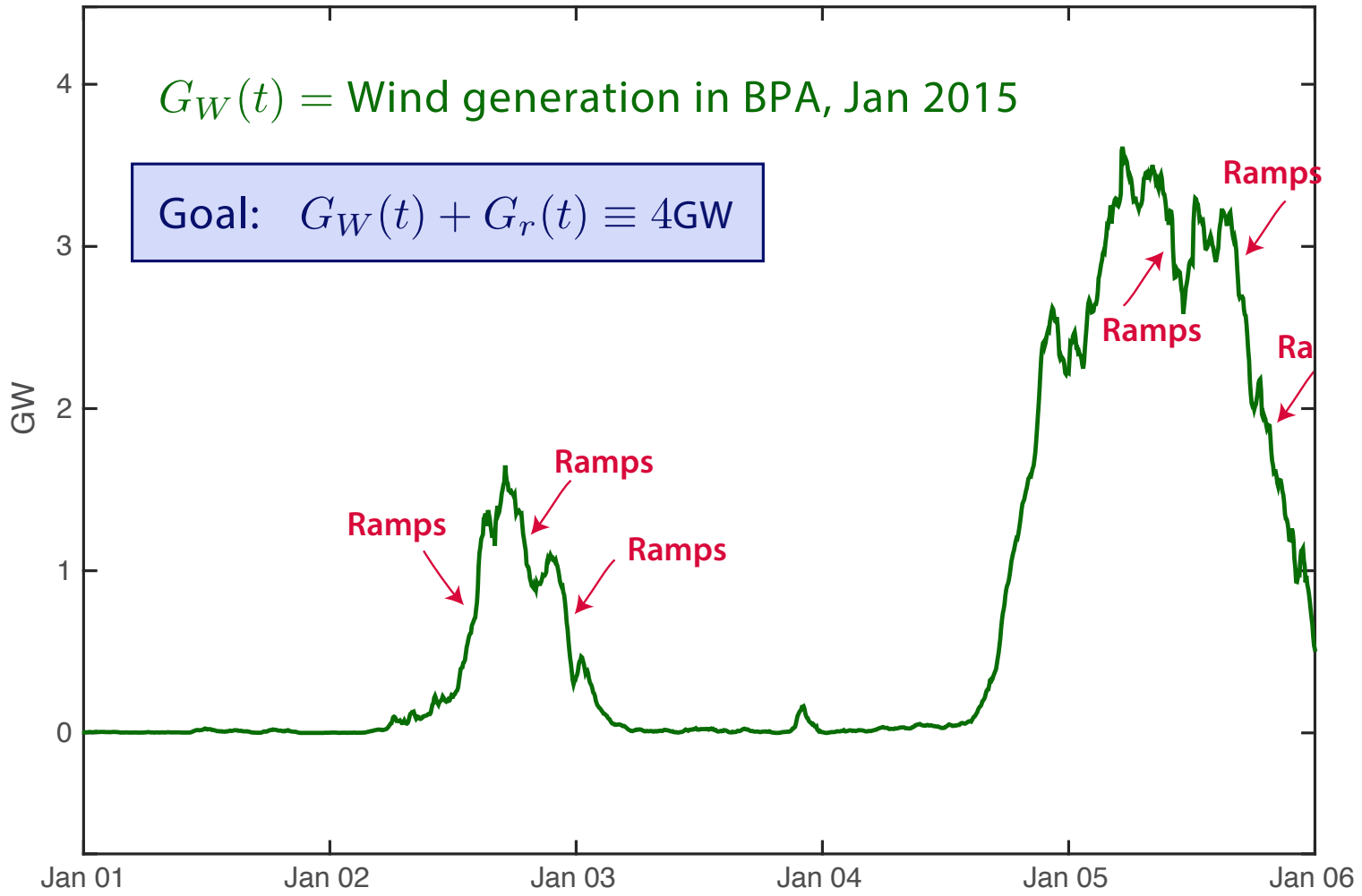
Frequency Decomposition

Regulation



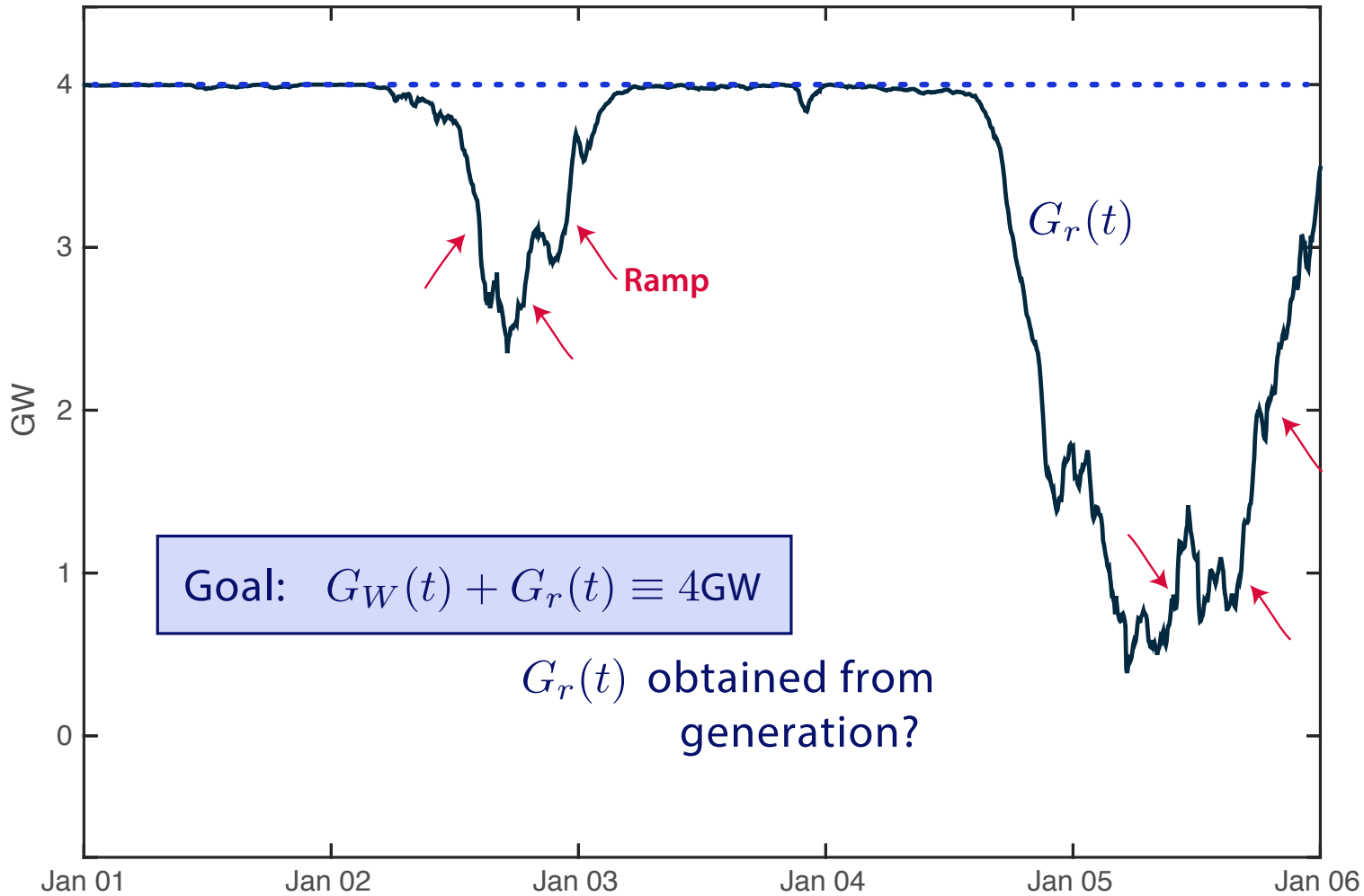
Frequency Decomposition

Regulation



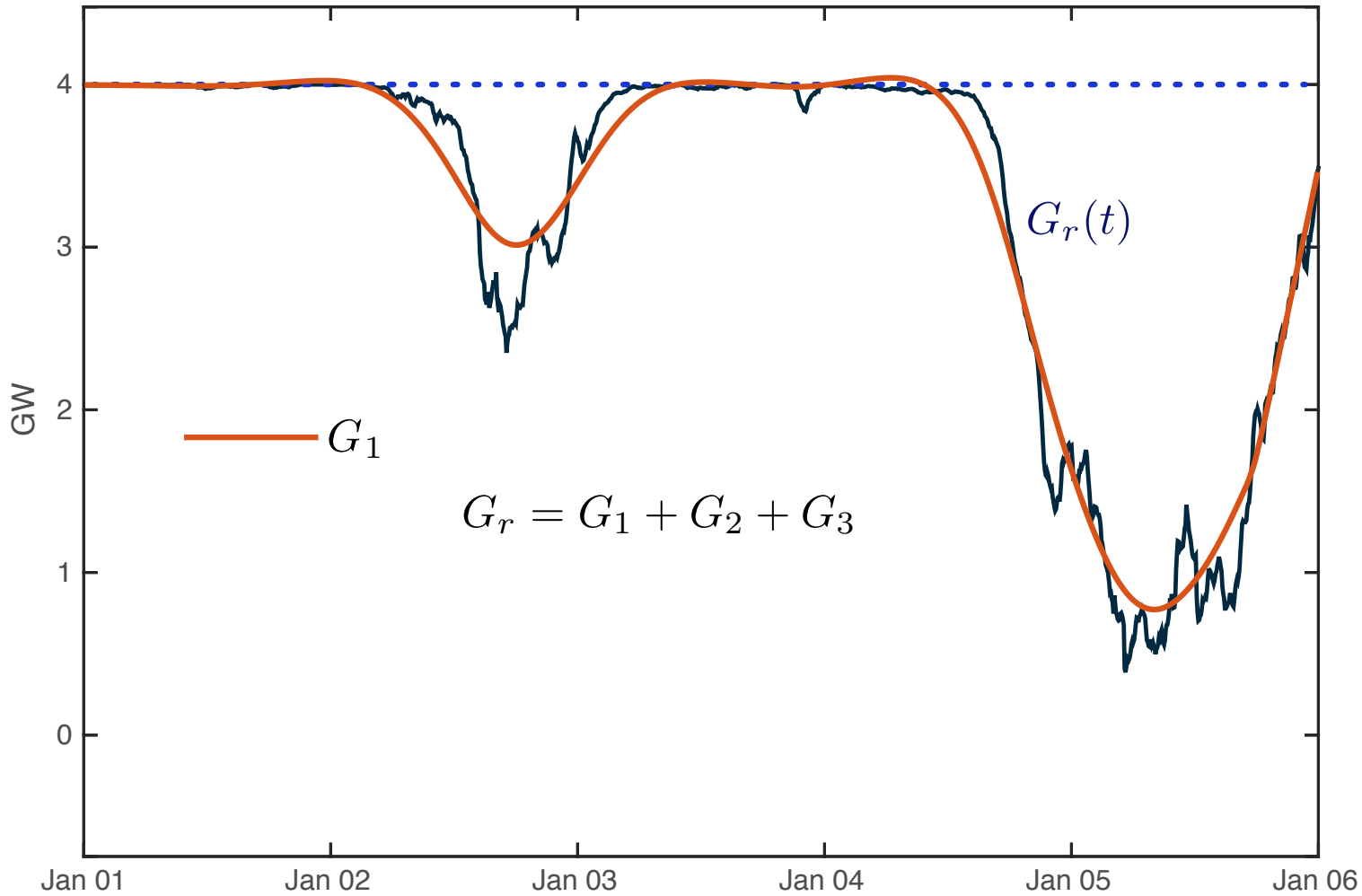
Frequency Decomposition

Regulation



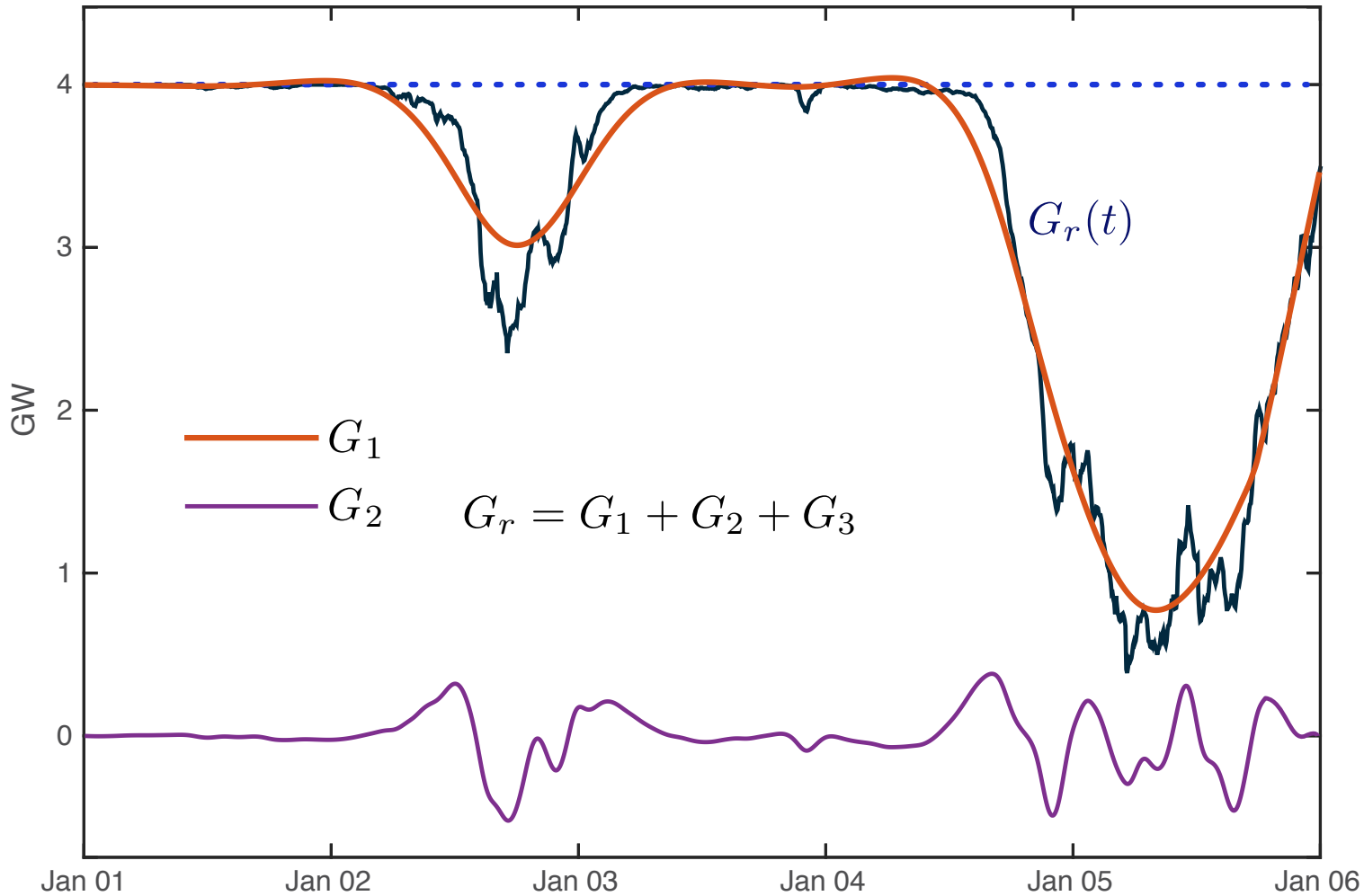
Frequency Decomposition

Regulation



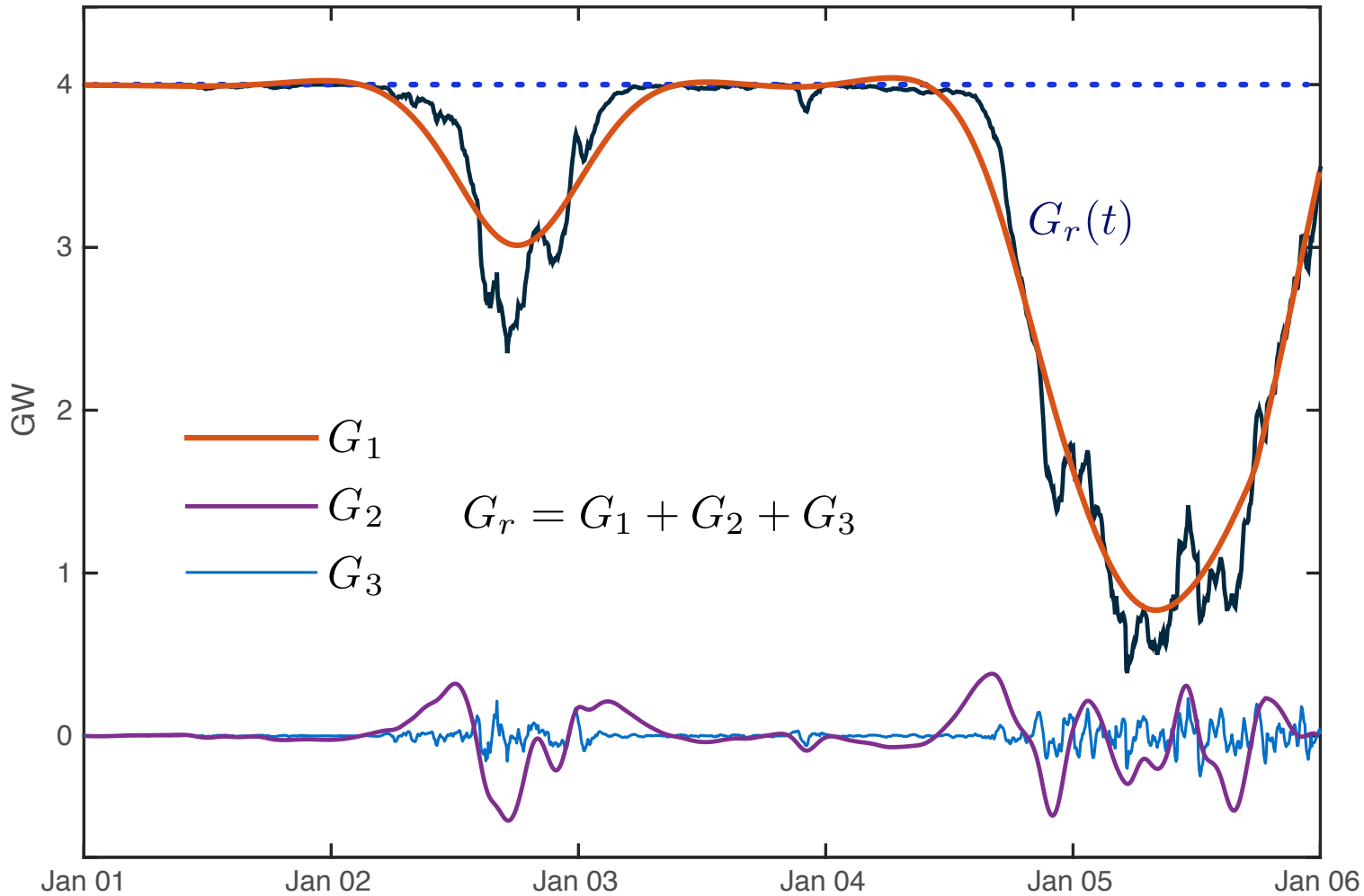
Frequency Decomposition

Regulation



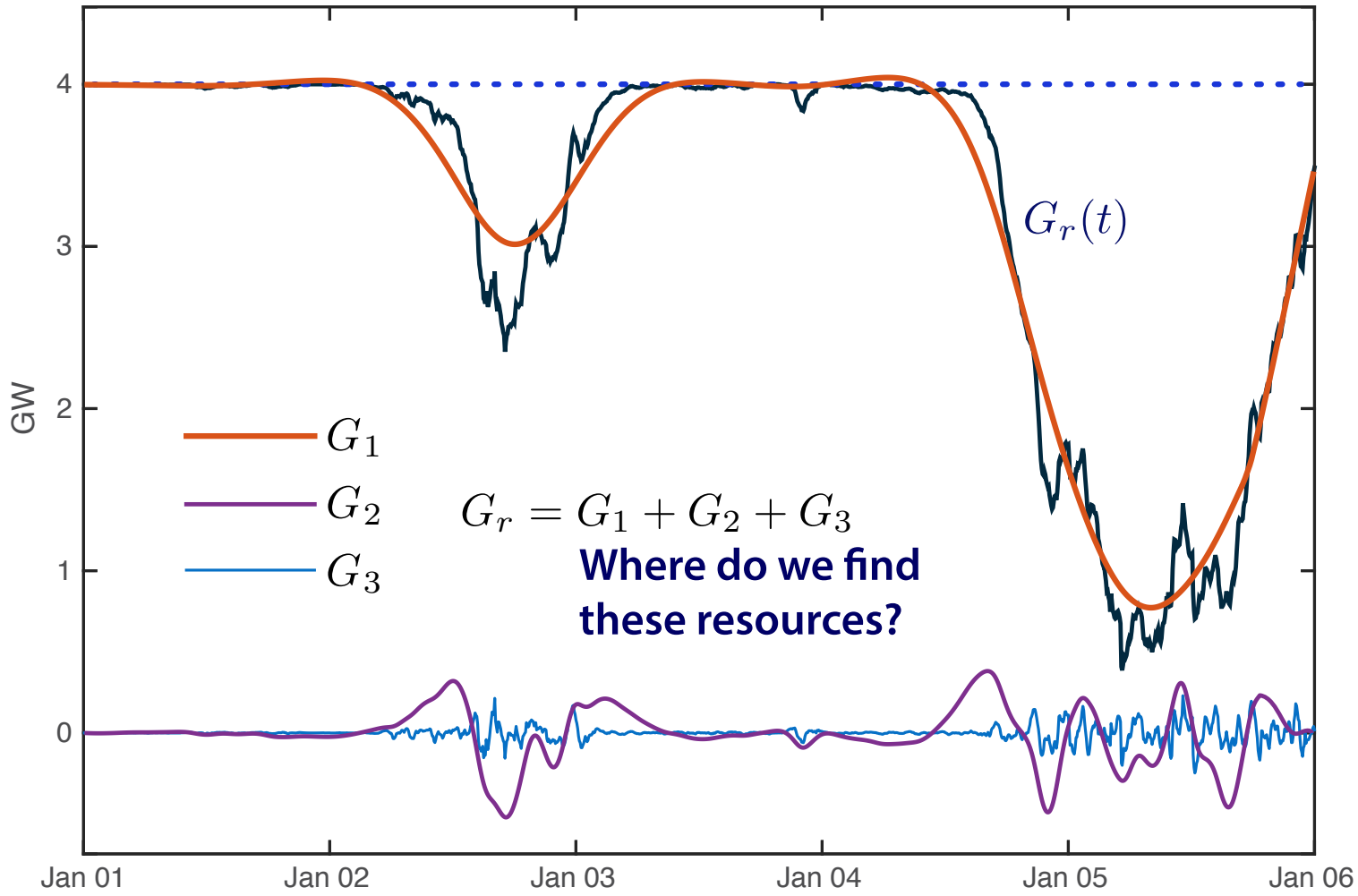
Frequency Decomposition

Regulation



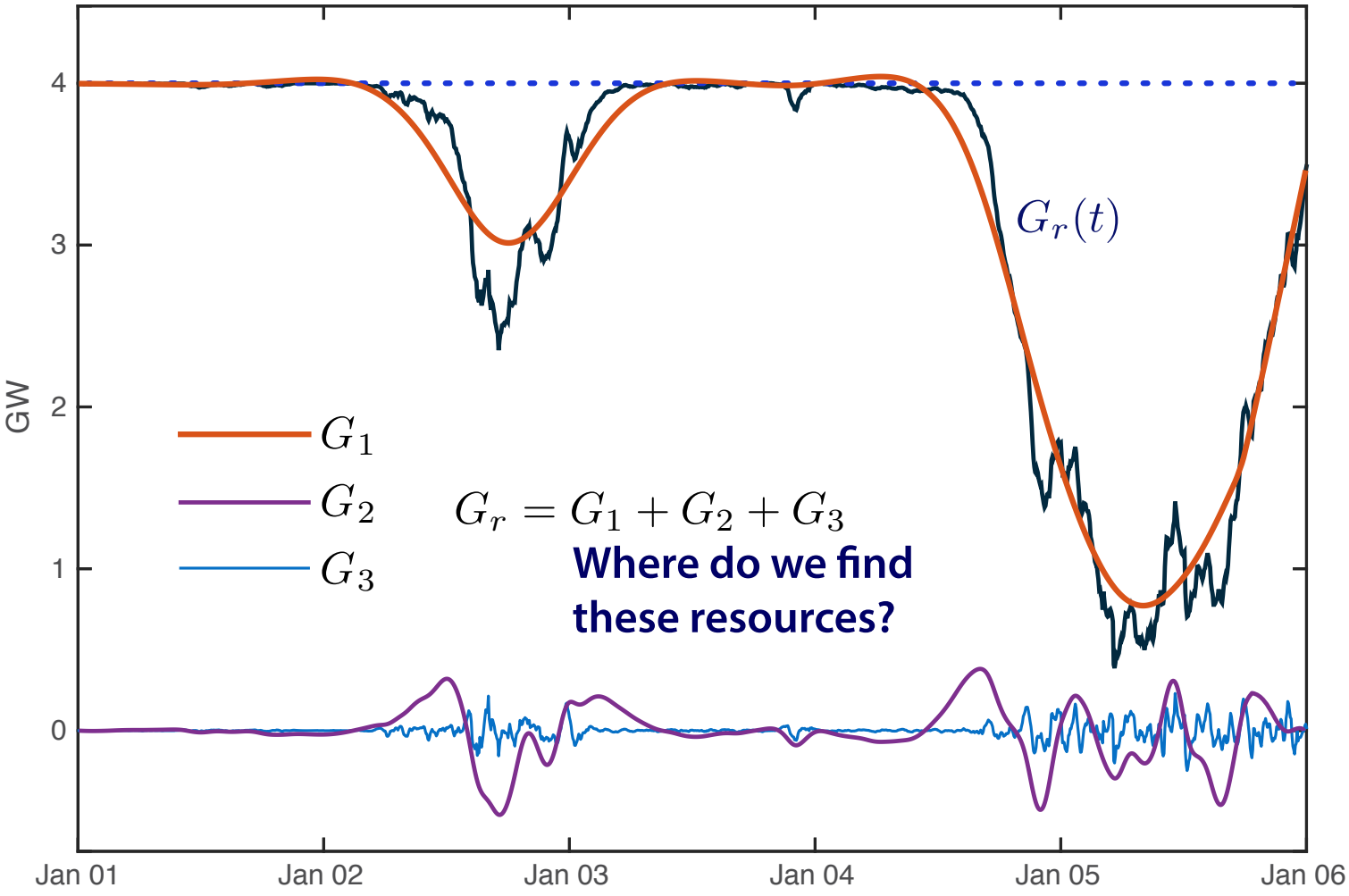
Frequency Decomposition

Regulation

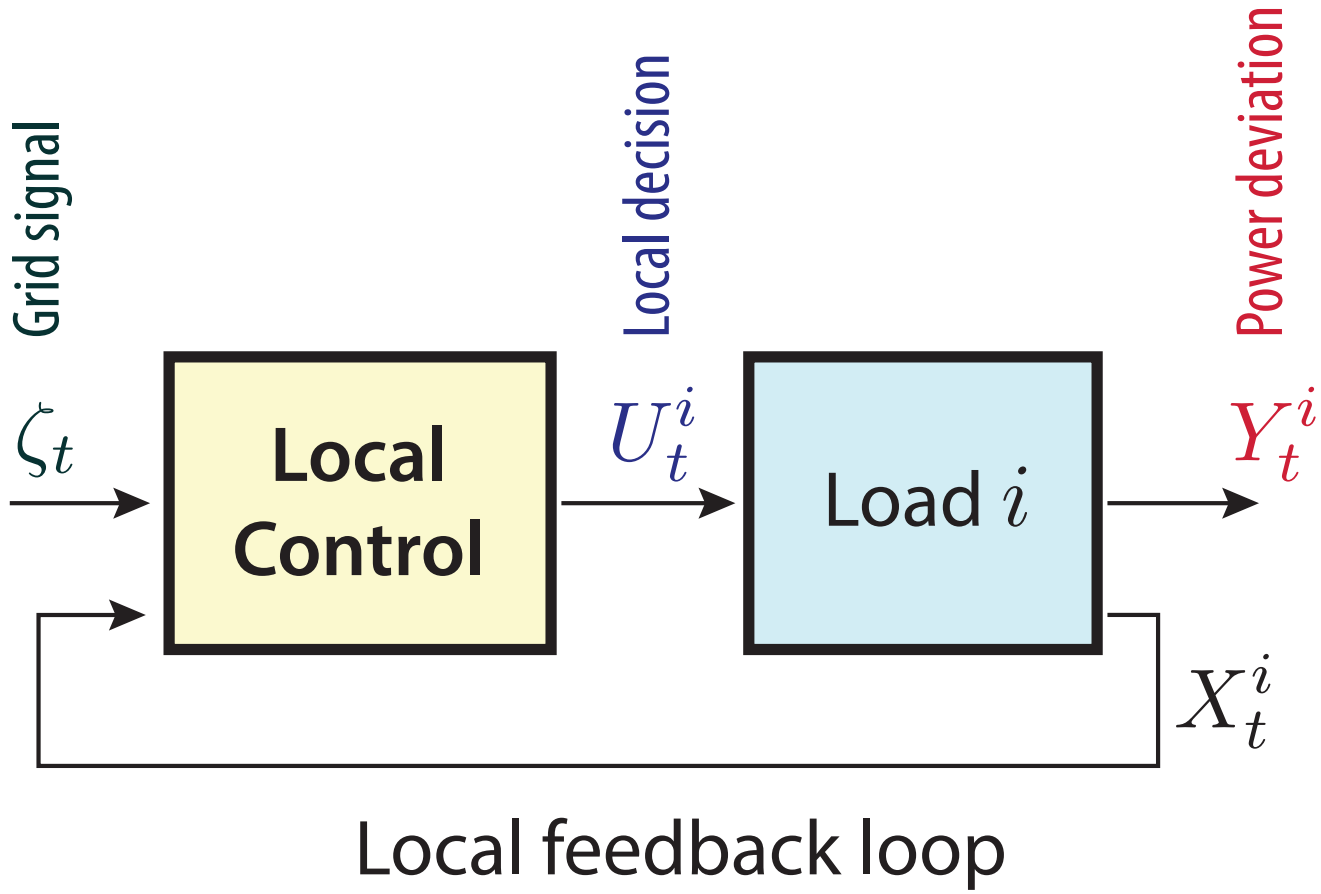


Frequency Decomposition

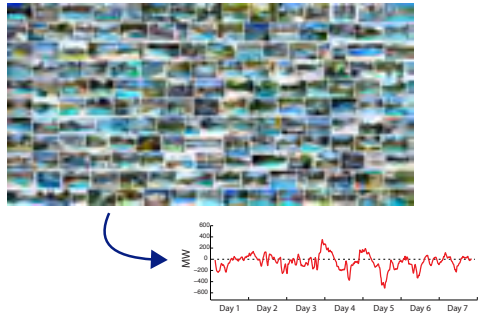
Regulation



These resources are free! Fans, Irrigation, pool pumps, ...

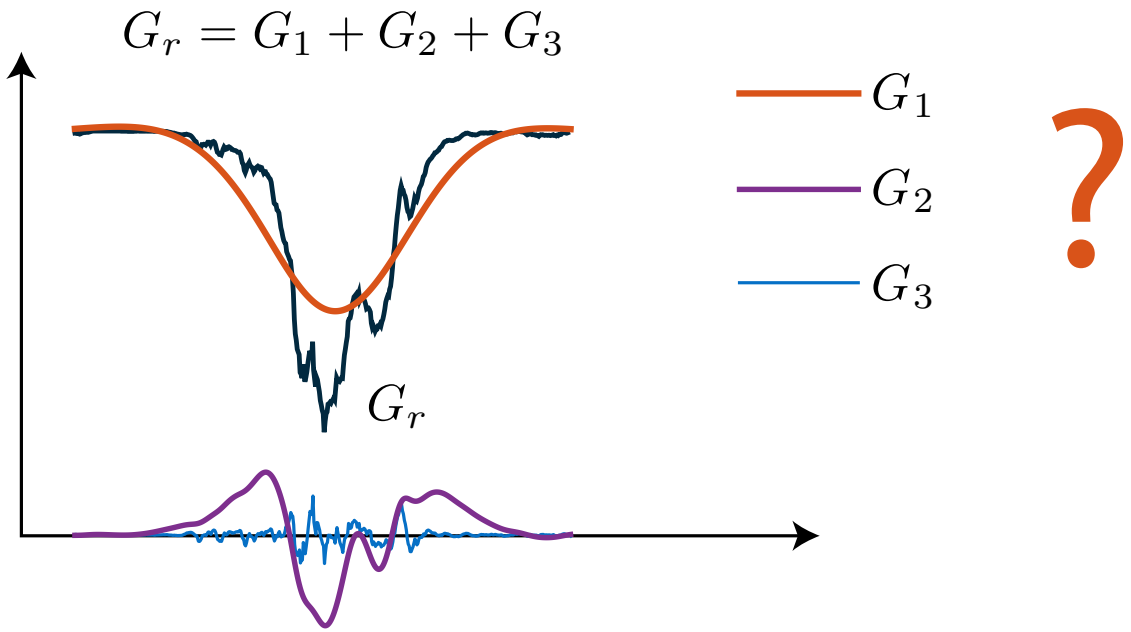


Demand Dispatch Design

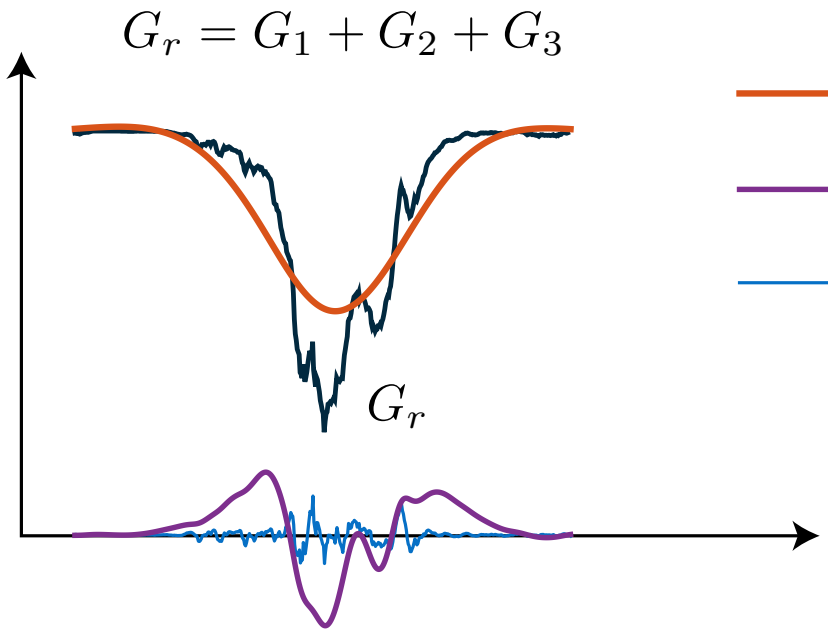


Demand Dispatch Design

Demand Dispatch



Demand Dispatch

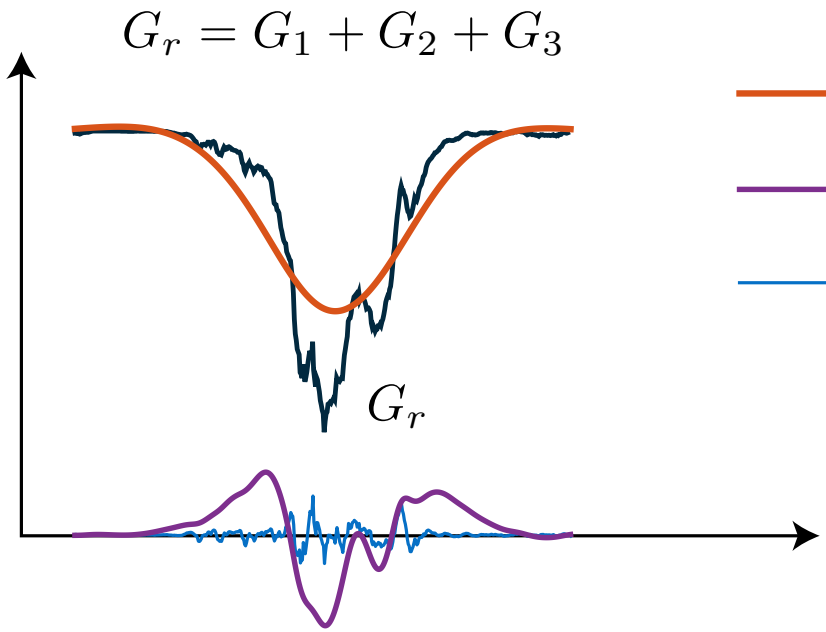


G_1 Traditional generation

G_2

G_3

Demand Dispatch



G_1 Traditional generation

G_2 Water pumping (e.g. pool pumps)

G_3 Fans in commercial HVAC

Demand Dispatch: Power consumption from loads varies automatically and continuously to provide service to the grid, without impacting QoS to the consumer

Demand Dispatch

Responsive Regulation *and* desired QoS

– A partial list of the needs of the grid operator, and the consumer

- High quality AS? (Ancillary Service)
- Reliable?
- Cost effective?
- Customer QoS constraints satisfied?

Demand Dispatch

Responsive Regulation *and* desired QoS

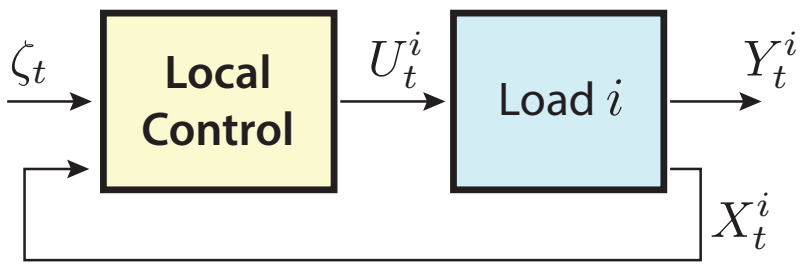
– A partial list of the needs of the grid operator, and the consumer

- High quality AS? (Ancillary Service)
- Reliable?
- Cost effective?
- Customer QoS constraints satisfied?

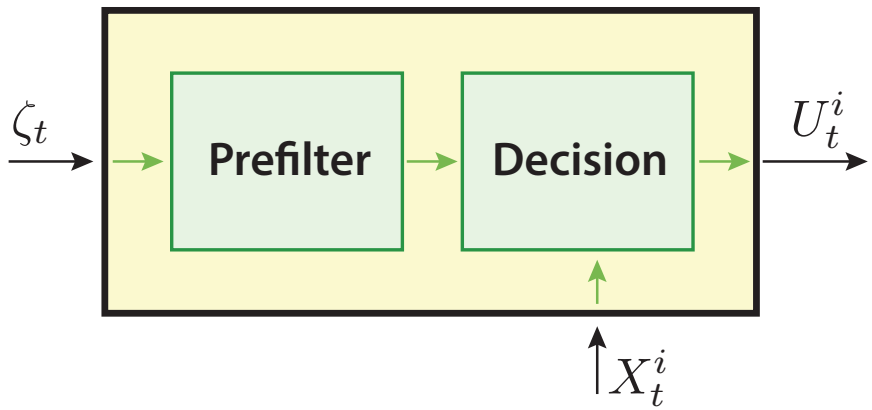
Demand Dispatch: achieve these goals simultaneously from flexible loads, through distributed control

General Principles for Design

Local feedback loop



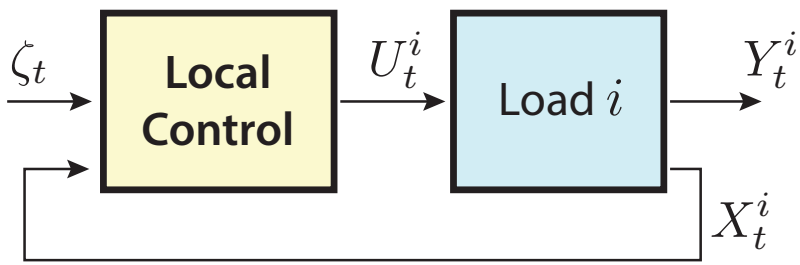
Two components to local control



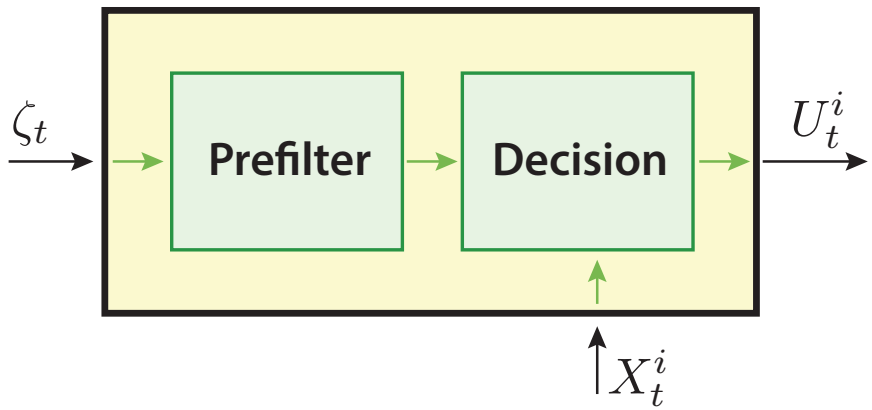
- Each load monitors its state and a regulation signal from the grid.

General Principles for Design

Local feedback loop



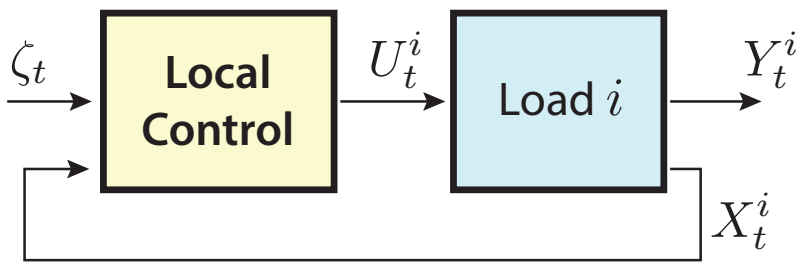
Two components to local control



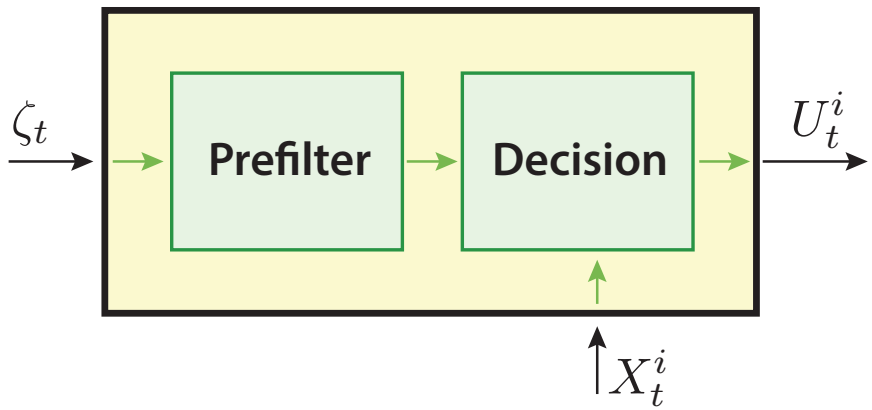
- Each load monitors its state and a regulation signal from the grid.
- Prefilter and decision rules designed to respect needs of load and grid

General Principles for Design

Local feedback loop



Two components to local control



- Each load monitors its state and a regulation signal from the grid.
- Prefilter and decision rules designed to respect needs of load and grid
- *Randomized policies* required for finite-state loads

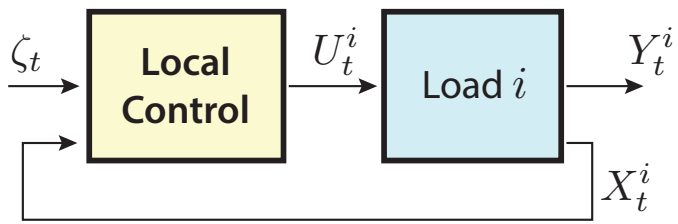
MDP model

MDP model

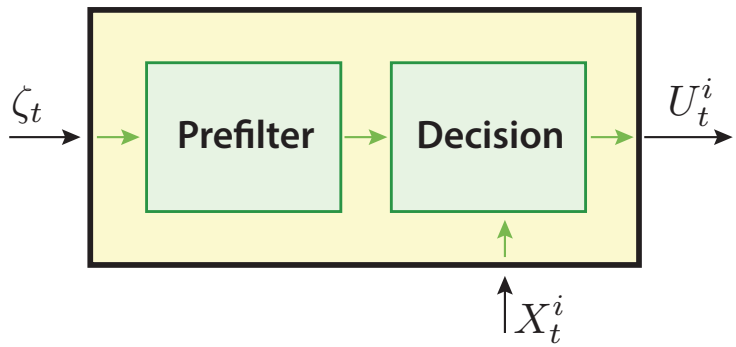
The state for a load is modeled as a controlled Markov chain.
Controlled transition matrix:

$$P_\zeta(x, x') = \mathsf{P}\{X_{t+1} = x' \mid X_t = x,\ \zeta_t = \zeta\}$$

Local feedback loop



Two components to local control



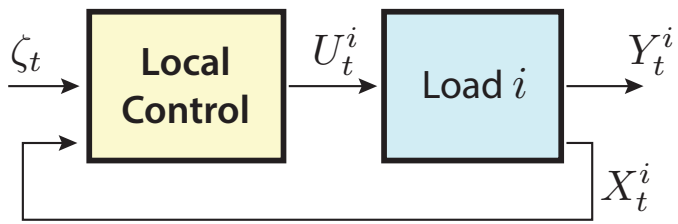
MDP model

MDP model

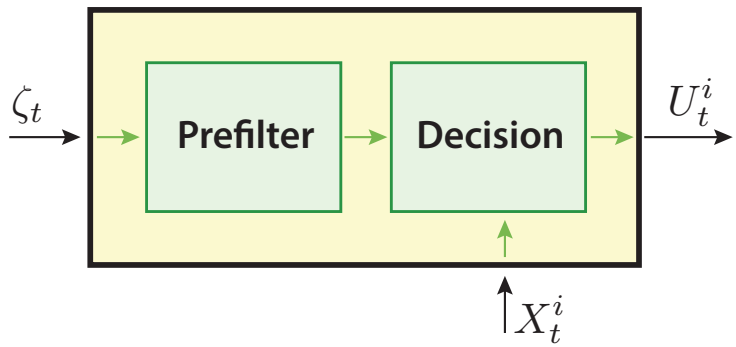
The state for a load is modeled as a controlled Markov chain.
Controlled transition matrix:

$$P_\zeta(x, x') = \mathsf{P}\{X_{t+1} = x' \mid X_t = x,\ \zeta_t = \zeta\}$$

Local feedback loop



Two components to local control



Questions:

- How to design P_ζ?
- How to analyze aggregate of similar loads?

How to analyze aggregate?

Mean field model, *R. Malhame et. al. 1984 –*

State process:

$$\mu_t(x) \approx \frac{1}{N} \sum_{i=1}^{N} \mathbb{I}\{X_t^i = x\}, \quad x \in \mathsf{X}$$

Evolution: $\mu_{t+1} = \mu_t P_{\zeta_t}$

How to analyze aggregate?

Mean field model, *R. Malhame et. al. 1984 –*

State process:

$$\mu_t(x) \approx \frac{1}{N} \sum_{i=1}^{N} \mathbb{I}\{X_t^i = x\}, \quad x \in \mathsf{X}$$

Evolution: $\mu_{t+1} = \mu_t P_{\zeta_t}$

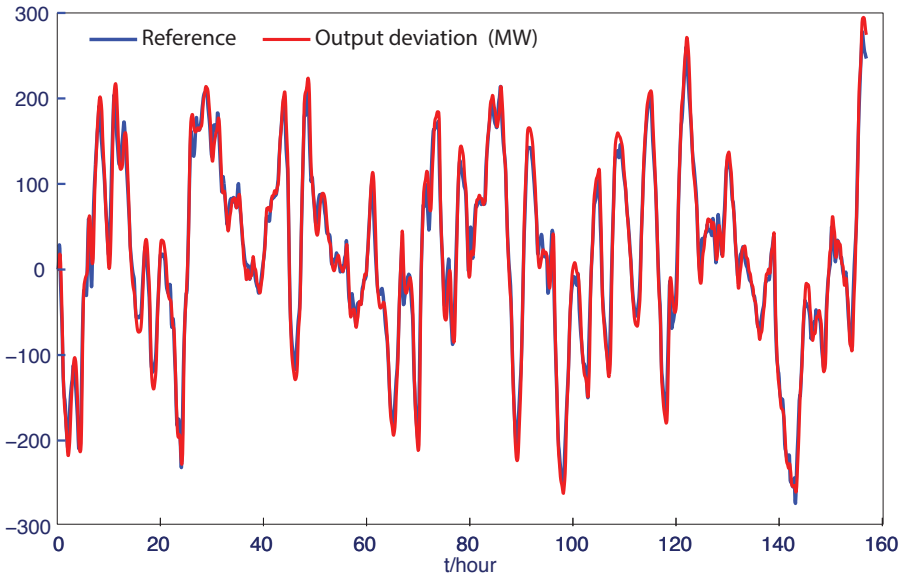
Output (mean power): $y_t = \sum_x \mu_t(x) \mathcal{U}(x)$

Nonlinear state space model

Linearization useful for control design

How to analyze aggregate?

Mean field model, *R. Malhame et. al. 1984 –*



State process:

$$\mu_t(x) \approx \frac{1}{N} \sum_{i=1}^{N} \mathbb{I}\{X_t^i = x\}, \quad x \in \mathsf{X}$$

Evolution: $\mu_{t+1} = \mu_t P_{\zeta_t}$

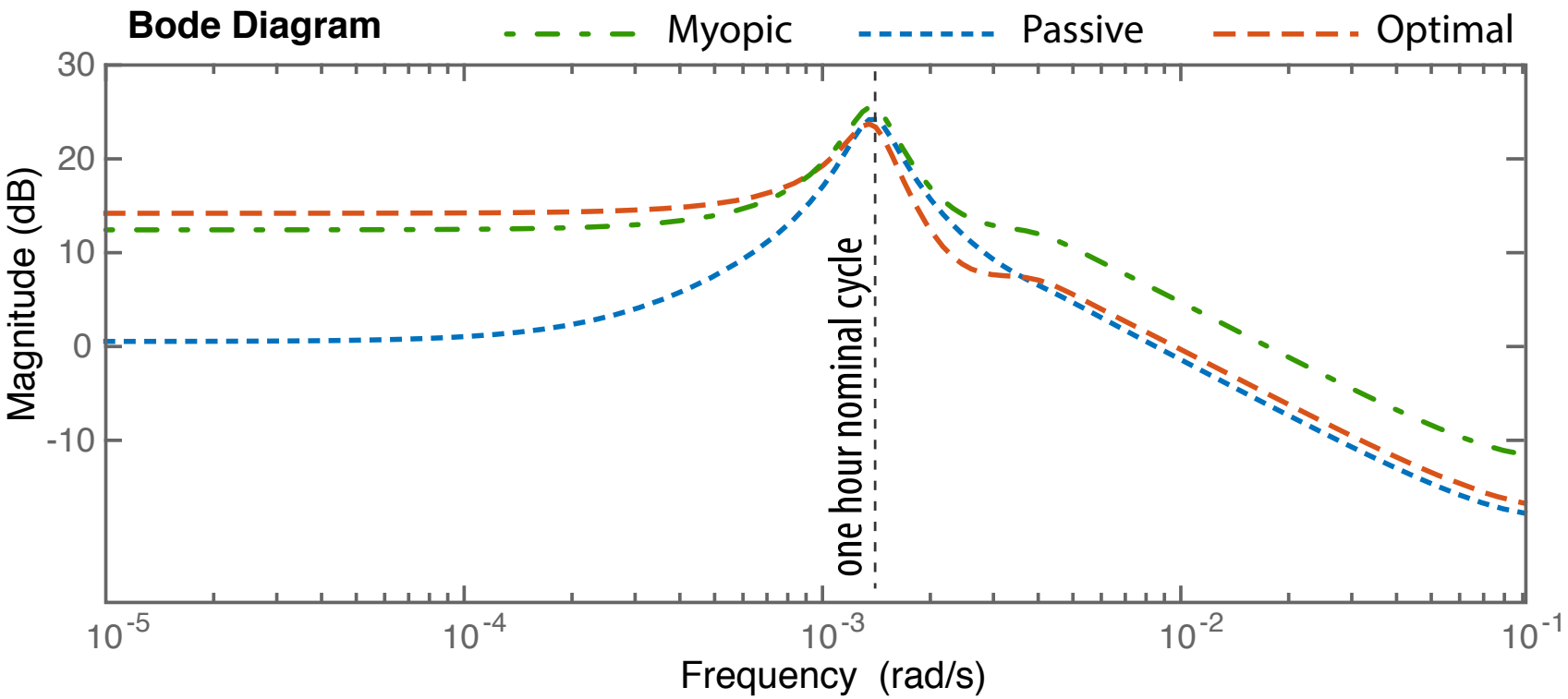
Output (mean power): $y_t = \sum_x \mu_t(x) \mathcal{U}(x)$

Nonlinear state space model

Linearization useful for control design

Nonlinear state space model: $\mu_{t+1} = \mu_t P_{\zeta_t}$, $y_t = \langle \mu_t, \mathcal{U} \rangle$

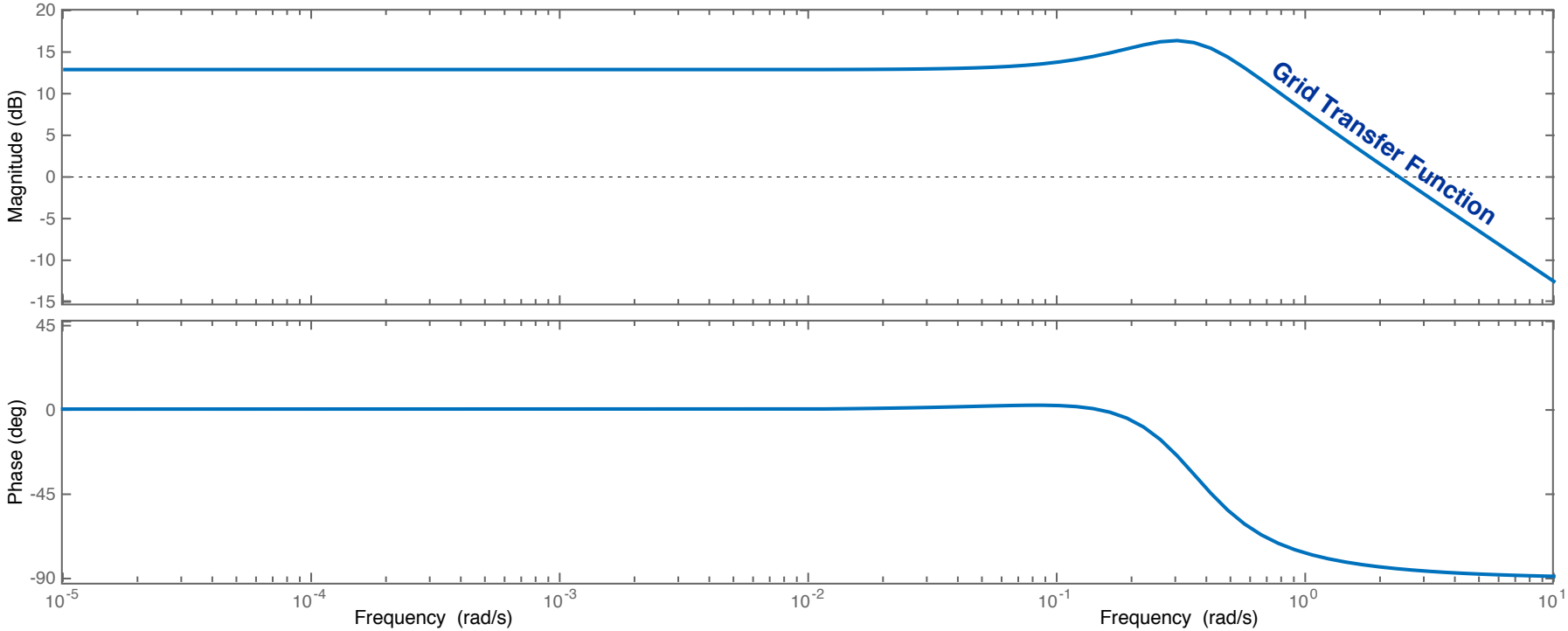
Linearization useful for control design



Three designs for a refrigerator: transfer function $\zeta_t \to y_t$

Control Architecture

Frequency *Allocation* for Demand Dispatch



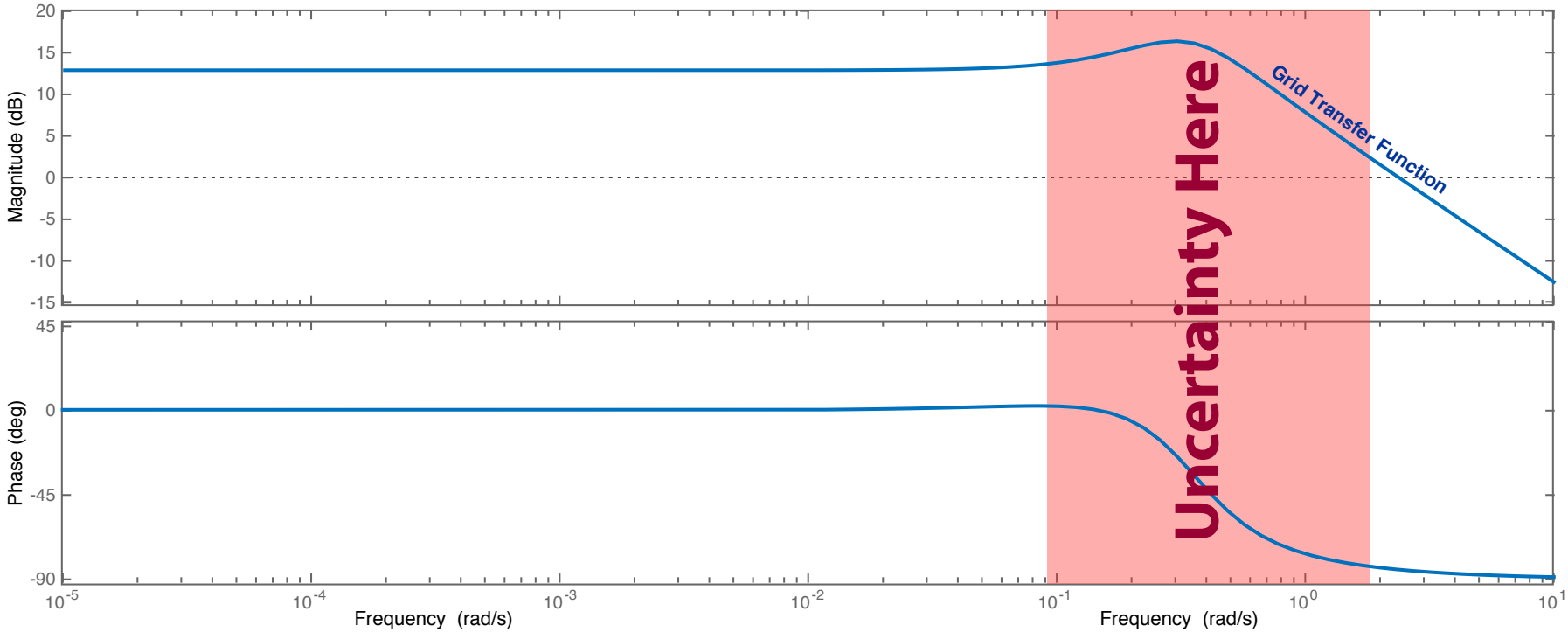
A typical macro model of the power grid

Motivation for PI control architecture, and **fear** of droop gain

H. Chavez, R. Baldick, and S. Sharma. Regulation adequacy analysis under high wind penetration scenarios in ERCOT nodal. IEEE Trans. on Sustainable Energy, 3(4):743–750, Oct 2012.

Control Architecture

Frequency *Allocation* for Demand Dispatch

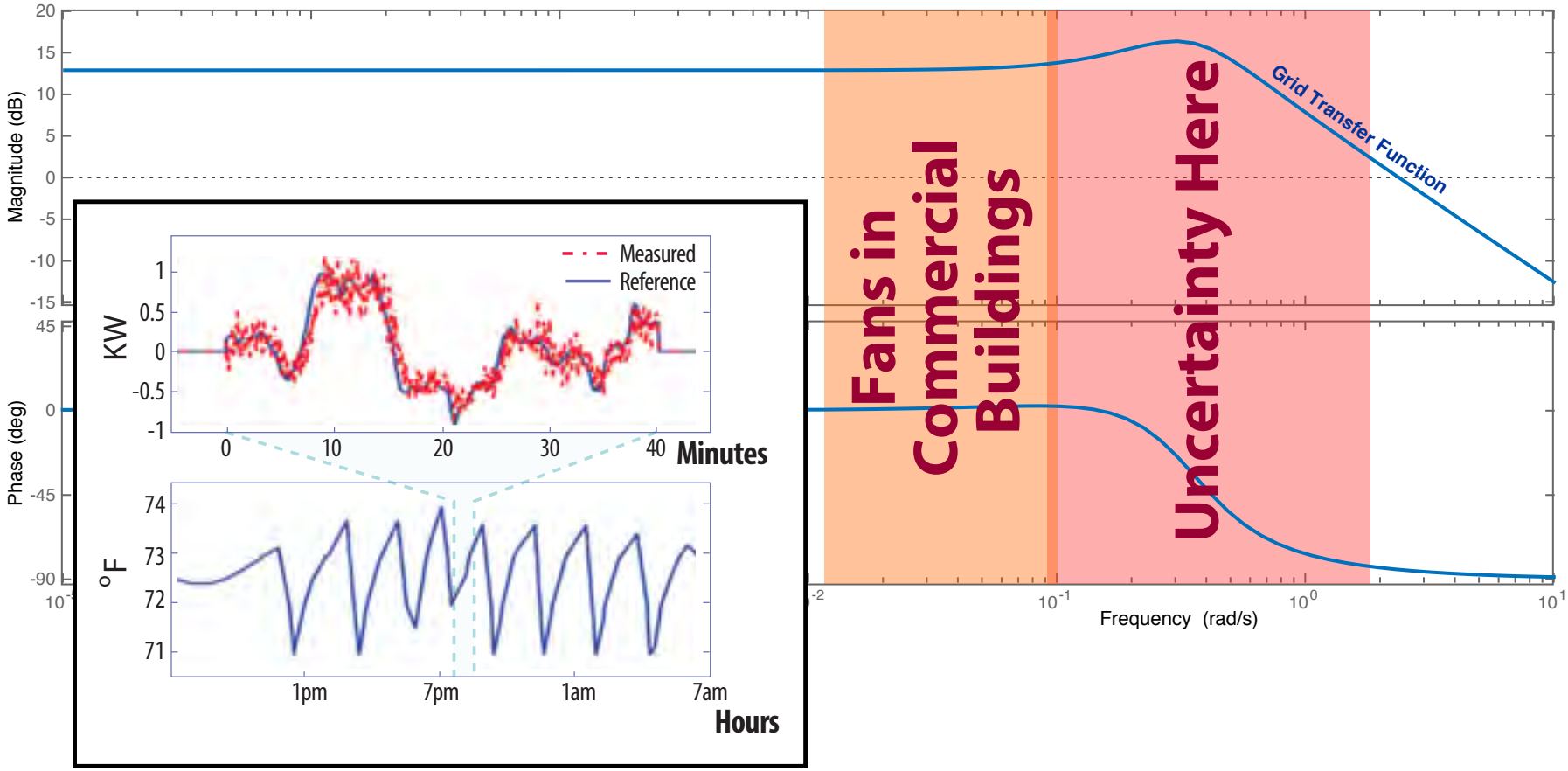


Fear is justified!

There is significant gain and phase uncertainty in this bandwidth

Control Architecture

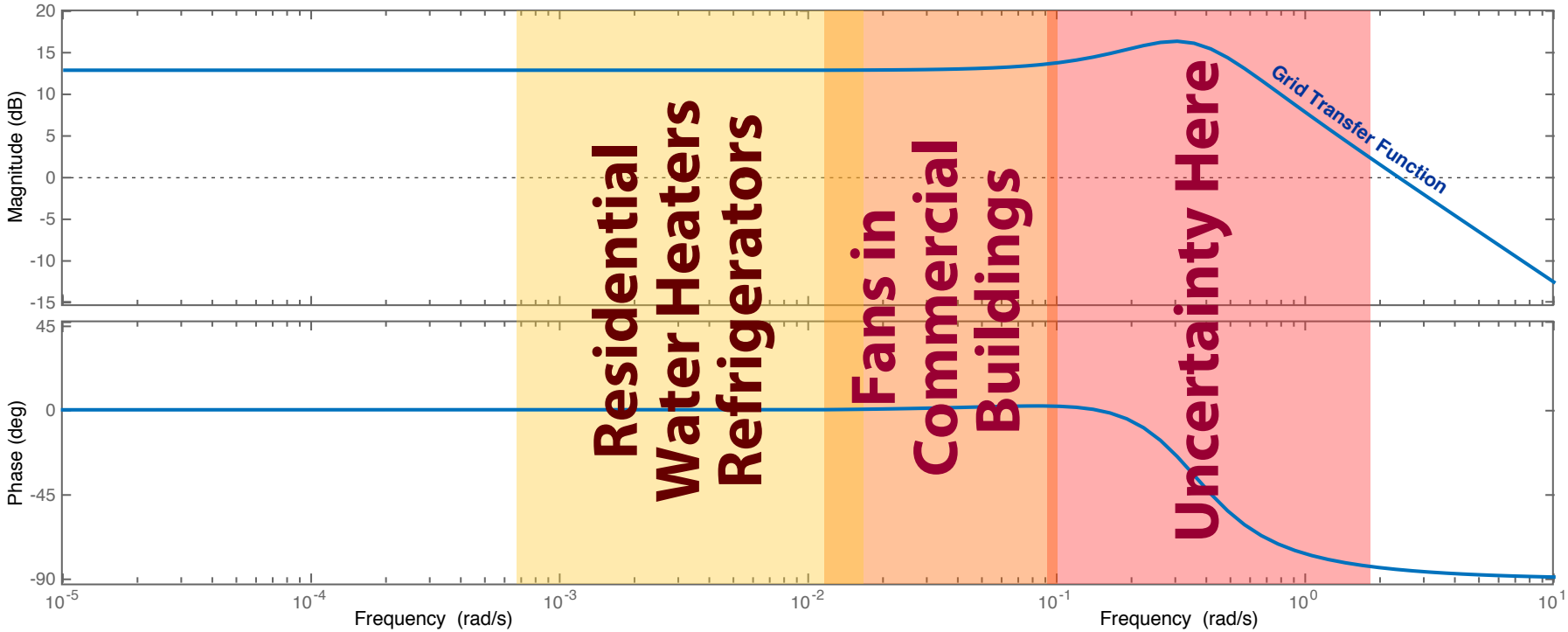
Frequency *Allocation* for Demand Dispatch



Fans in commercial buildings in the state of Florida
can supply all of the RegD and RegA regulation needs of PJM

Control Architecture

Frequency *Allocation* for Demand Dispatch

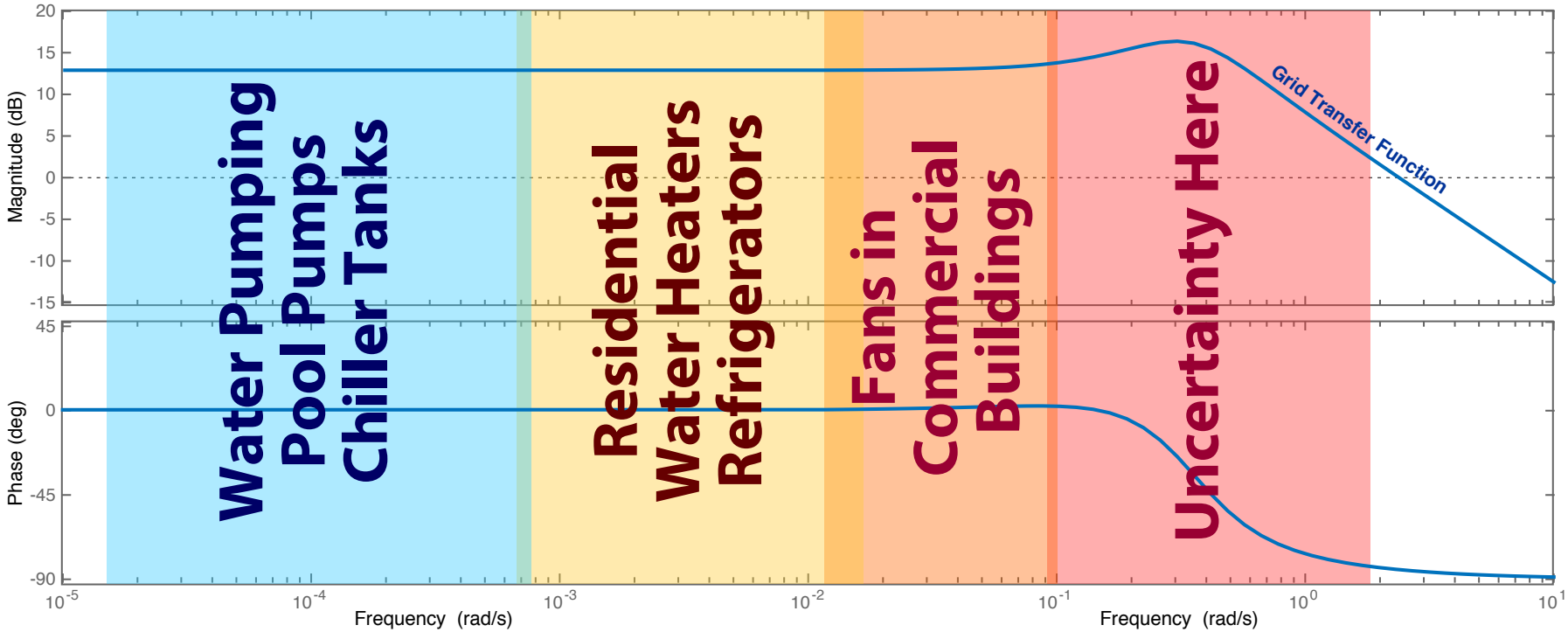


The bandwidth of these devices is centered around their natural cycle

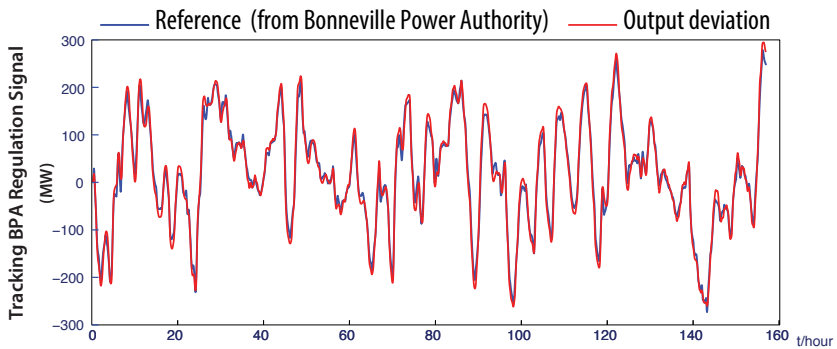
the capacity is enormous in this bandwidth

Control Architecture

Frequency *Allocation* for Demand Dispatch



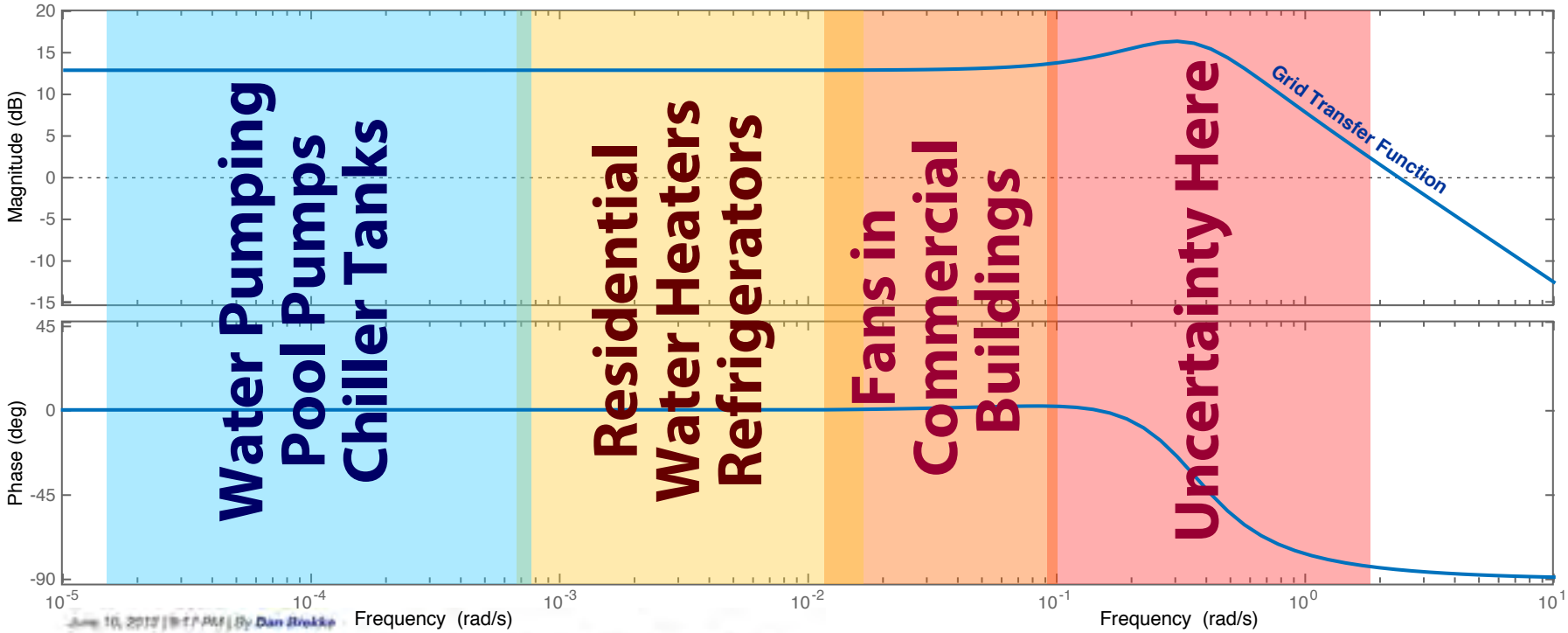
10,000 pools



Bandwidth centered around its natural cycle

Control Architecture

Frequency *Allocation* for Demand Dispatch



19%: The Great Water-Power Wake-Up Call

FILED UNDER: Power, Water, water and power

17 Comments Tweet Recommend

WATER NEEDS POWER

Ever wonder how much juice it takes to move water?

Explore the ***Water and Power series*** *and hear Dan's story on KQED's* **The California Report**.

When you open that faucet, it's more than water that's flowing.

19% of the load

Imagine the capacity from water pumping in California?

Information Architecture: $\zeta_t = f(?)$

Focus of recent research

$\zeta = f(\Delta\omega)$	grid freq	(Schweppe ...)
$\zeta = f(y)$	load *power*	(Inria/UF 2013+)
$\zeta = f(\mu)$	load *histogram*	(Montreal/Berkeley/Mich)

Information Architecture: $\zeta_t = f(?)$

Focus of recent research

$\zeta = f(\Delta\omega)$	grid freq	(Schweppe ...)
$\zeta = f(y)$	load *power*	(Inria/UF 2013+)
$\zeta = f(\mu)$	load *histogram*	(Montreal/Berkeley/Mich)

Distributed control design includes local filter:

- Filtering at each load to create homogeneous response
- Aggregate behaves as a perfect battery *in a limited bandwidth*

By design: Balancing authority requires only grid-level information.

Information Architecture: $\zeta_t = f(?)$

Focus of recent research

$\zeta = f(\Delta\omega)$	grid freq	(Schweppe ...)
$\zeta = f(y)$	load *power*	(Inria/UF 2013+)
$\zeta = f(\mu)$	load *histogram*	(Montreal/Berkeley/Mich)

Distributed control design includes local filter:

- Filtering at each load to create homogeneous response
- Aggregate behaves as a perfect battery *in a limited bandwidth*

By design: Balancing authority requires only grid-level information.

Two warnings:

- High frequency AS (primary control) is not included in these studies
- Phase lag and delay for low frequency AS **may** induce cost because of additional AS required

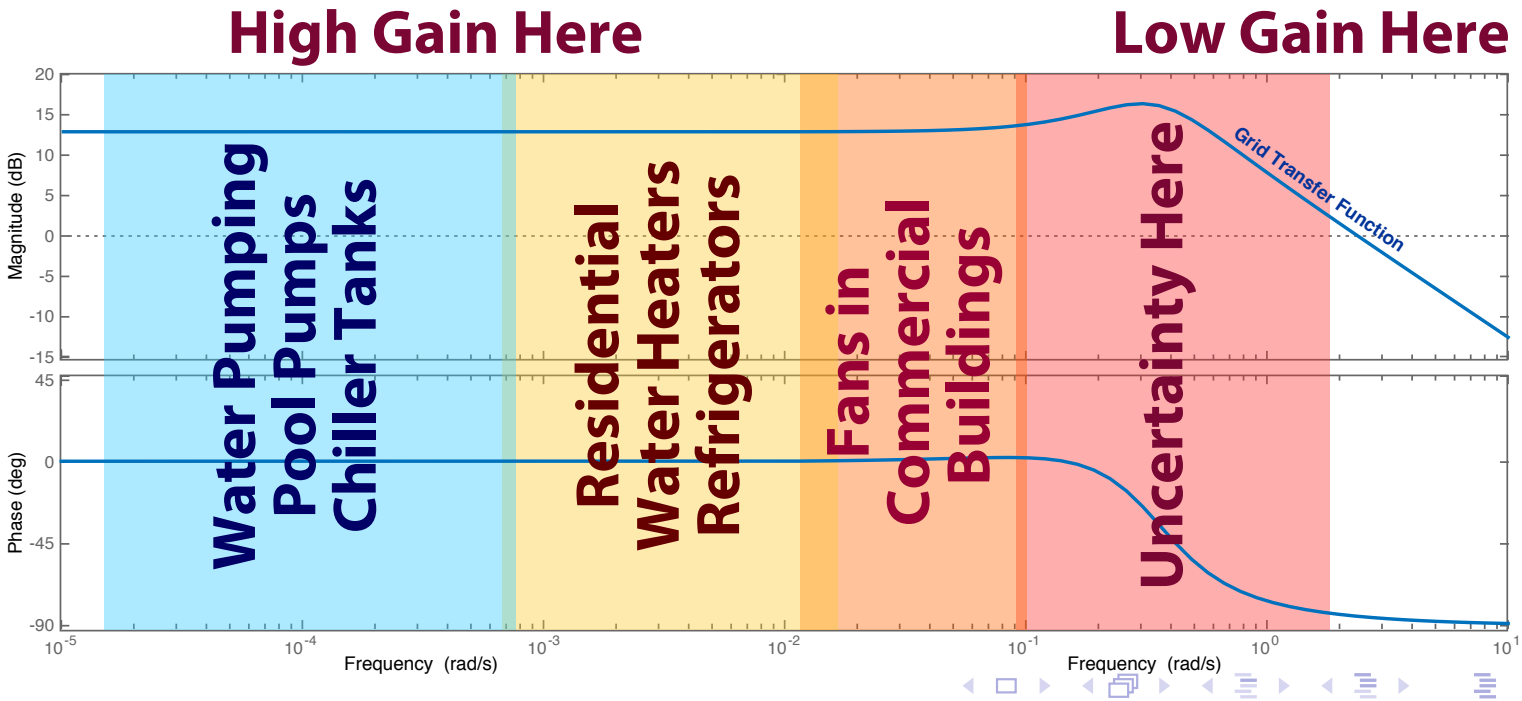
Information Architecture: $\zeta_t = f(?)$

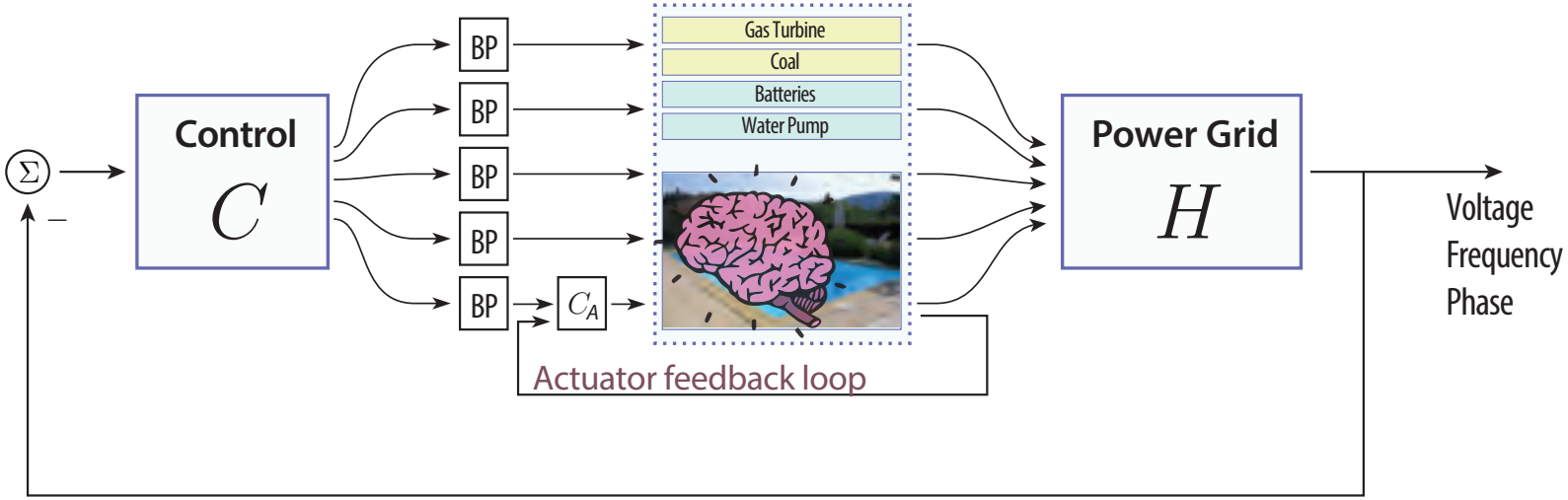
Analysis: Classical control design

- Filtering at each load to create homogeneous response
- Aggregate behaves as a perfect battery *in a limited bandwidth*

By design: Balancing authority requires only grid-level information.

Balancing Authority wants





Conclusions

Conclusions

The virtual storage capacity from demand dispatch is enormous

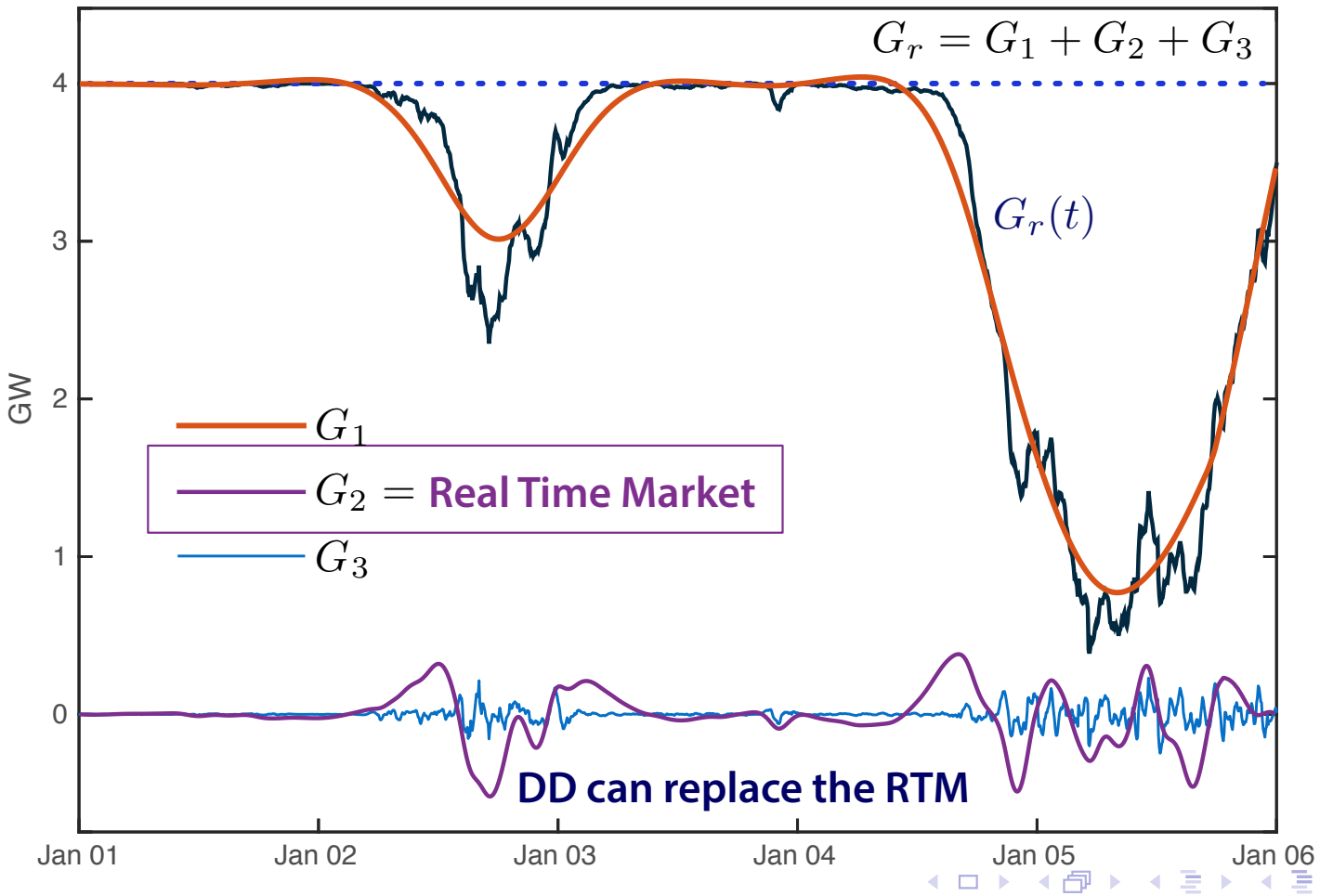
With appropriate filtering and local control, DD can provide excellent ancillary service, even without two-way communication.

Bandwidth ranges from AGC to RTM!

Conclusions

The virtual storage capacity from demand dispatch is enormous

These resources are **free!** Fans, Irrigation, pool pumps, ...
Demand-side resources could replace our real-time markets!



Conclusions

The virtual storage capacity from demand dispatch is enormous

These resources are **free!** Fans, Irrigation, pool pumps, ...

Not so fast!

Conclusions

The virtual storage capacity from demand dispatch is enormous

These resources are **free!** Fans, Irrigation, pool pumps, ...

Not so fast! Zero marginal cost $\neq$ **free**

Conclusions

The virtual storage capacity from demand dispatch is enormous

These resources are **free!** Fans, Irrigation, pool pumps, ...

Not so fast! Zero marginal cost $\neq$ **free**

Conclusions

- Ancillary Service can be *as free as Digital Music*

Conclusions

The virtual storage capacity from demand dispatch is enormous

These resources are **free!** Fans, Irrigation, pool pumps, ...

Not so fast! Zero marginal cost $\neq$ **free**

Conclusions

- Ancillary Service can be *as free as Digital Music*
- However, as often happens in power systems, as well as music, there is a *huge sunk-cost*

Conclusions

The virtual storage capacity from demand dispatch is enormous

These resources are **free!** Fans, Irrigation, pool pumps, ...

Not so fast! Zero marginal cost $\neq$ **free**

Conclusions

- Ancillary Service can be *as free as Digital Music*
- However, as often happens in power systems, as well as music, there is a *huge sunk-cost*
- Challenge: economic theory for the music industry

Conclusions

The virtual storage capacity from demand dispatch is enormous

These resources are **free!** Fans, Irrigation, pool pumps, ...

Not so fast! Zero marginal cost $\neq$ **free**

Conclusions

- Ancillary Service can be *as free as Digital Music*
- However, as often happens in power systems, as well as music, there is a *huge sunk-cost*
- Challenge: economic theory for the music industry

FERC Order 755 is a nice start.

Conclusions

The virtual storage capacity from demand dispatch is enormous

These resources are **free!** Fans, Irrigation, pool pumps, ...

Not so fast! Zero marginal cost $\neq$ **free**

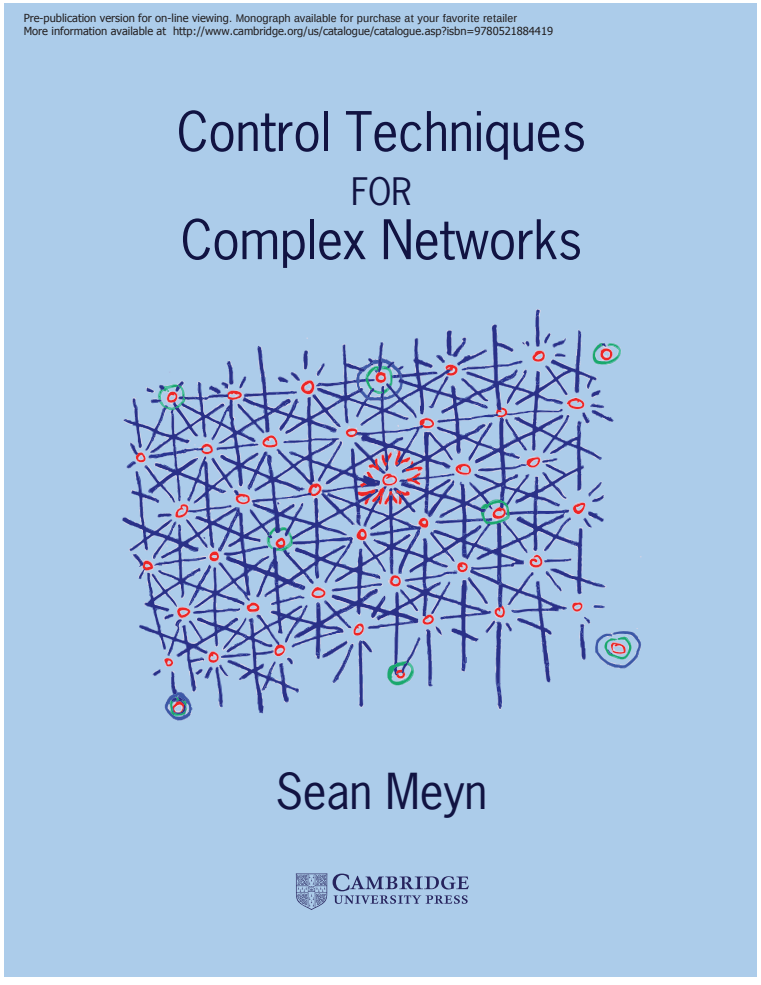
Conclusions

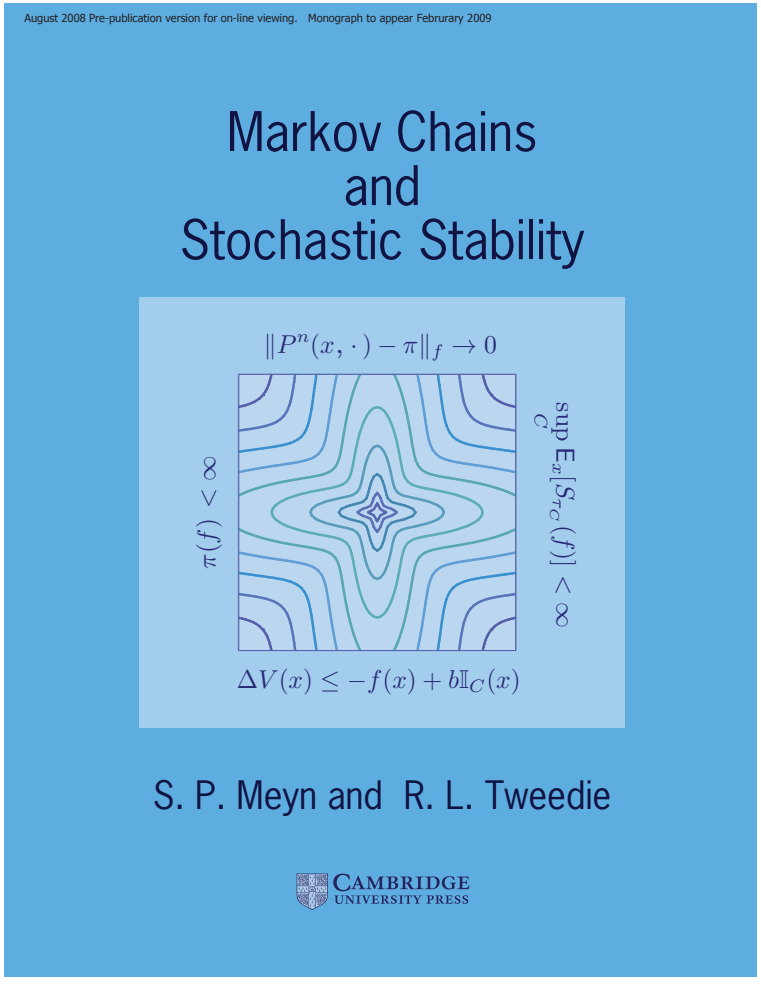
- Ancillary Service can be *as free as Digital Music*
- However, as often happens in power systems, as well as music, there is a *huge sunk-cost*
- Challenge: economic theory for the music industry

FERC Order 755 is a nice start.

Will the Supreme Court give us a new and improved FERC Order 745 in the spring?

Conclusions


Pre-publication version for on-line viewing. Monograph available for purchase at your favorite retailer
More information available at http://www.cambridge.org/us/catalogue/catalogue.asp?isbn=9780521884419
Control Techniques
FOR
Complex Networks
Sean Meyn
CAMBRIDGE
UNIVERSITY PRESS


August 2008 Pre-publication version for on-line viewing. Monograph to appear Februrary 2009
Markov Chains
and
Stochastic Stability
$\|P^n(x,\cdot) - \pi\|_f \to 0$
$\pi(f) < \infty$
$\sup_C \mathsf{E}_x[S_{\tau_C}(f)] < \infty$
$\Delta V(x) \le -f(x) + b\mathbb{I}_C(x)$
S. P. Meyn and R. L. Tweedie
CAMBRIDGE
UNIVERSITY PRESS

References

Selected References

More at www.meyn.ece.ufl.edu

H. Hao, T. Middelkoop, P. Barooah, and S. Meyn. How demand response from commercial buildings will provide the regulation needs of the grid. In *50th Allerton Conference on Communication, Control, and Computing*, pages 1908–1913, 2012.

H. Hao, Y. Lin, A. Kowli, P. Barooah, and S. Meyn. Ancillary service to the grid through control of fans in commercial building HVAC systems. *IEEE Trans. on Smart Grid*, 5(4):2066–2074, July 2014.

S. Meyn, P. Barooah, A. Bušić, Y. Chen, and J. Ehren. Ancillary service to the grid using intelligent deferrable loads. *IEEE Trans. Automat. Control*, 60(11):2847–2862, Nov 2015.

P. Barooah, A. Bušić, and S. Meyn. Spectral decomposition of demand-side flexibility for reliable ancillary services in a smart grid. In *Proc. 48th Annual Hawaii International Conference on System Sciences (HICSS)*, pages 2700–2709, Kauai, Hawaii, 2015.

Y. Chen, A. Bušić, and S. Meyn. Individual risk in mean-field control models for decentralized control, with application to automated demand response. In *Proc. of the 53rd IEEE Conference on Decision and Control*, pages 6425–6432, Dec. 2014.

J. Mathias, R. Kaddah, A. Bušić, and S. Meyn. Smart fridge / dumb grid? demand dispatch for the power grid of 2020. In *Proc. 49th Annual Hawaii International Conference on System Sciences (HICSS)*, and ArXiv e-prints:1509.01531 (2015).